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Final Report DRI No. 2026

Contract No. AF 19(604)-2204

1 November 1961

STUDY OF GEOMAGNETIC FLUCTUATIONS (1 TO 50 CPS)

Project 8601

Task 86013

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GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

AFCRL-62-238

FINAL REPORT
STUDY OF GEOMAGNETIC FLUCTUATIONS (1 TO 50 CPS)

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Contract No. AF 19(604)-2204

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ABSTRACT

A continuing study of fluctuations of the earth's magnetic field is described. Its purpose has been to record and analyze fluctuations within the frequency range 1 to 50 cycles per second. Analysis is directed toward relating these fluctuations to specific causes. Three orthogonal components are recorded. Data has been obtained for various periods up to a year or more from individual recording stations at College, Alaska; Ft. Devens, Massachusetts; Thule, Greenland; Mt. Evans, Colorado; Huancayo, Peru; and Shickley, Nebraska. Reduction of data to digital form is accomplished by a semi-automatic data-processing system. Output of the system is a series of numbers representing mean hourly activity within six one-octave bands for each component. These bands are centered at 1.5, 2.75, 5.0, 10.0, 20.0 and 40.0 cycles per second.

Part of the available data has been reduced and a start made on its analysis. There appears to be a positive correlation between meteor activity and geomagnetic fluctuations in the 1 to 2 cycle per second range, which is to be studied further.

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I. INTRODUCTION

The purpose of the work which has been done under Contract AF 19(604)-2204 is to detect, record, measure, and analyze fluctuations of the earth's magnetic field which occur within the sub-audio-frequency range 1 to 50 cycles per second. The work is directed toward relating the observed fluctuation data to specific causes and to other geophysical phenomena.

The impetus for this study originated with Dr. A. Raymond Jordan of DRI and Mr. Elwood Maple of Air Force Cambridge Research Laboratories. Work was formally initiated in January 1957, to be coordinated with overall IGY planning. Recording stations were established in Puerto Rico (Jan. 1958), Alaska (March 1958), Fort Devens, Mass. (May 1958), Thule, Greenland (June 1958), Mt. Evans, Colorado (July 1958), Huancayo, Peru (March 1960), and Shickley, Nebraska (Feb. 1961). Equipment from the Thule station was modified and sent in November 1960 to establish a station in Antarctica. Weather and supply problems prevented this, but the station should be activated by late 1961. The locations of all recording stations are given in Figure 1.

Three components of the variation of the earth's field are sensed. They are the X, Y, and Z components (North-South, East-West, and vertical). The fluctuations sought are of the order of 0.1 to 10 milligamma*, and have to be measured in the presence of the earth's static field, of the order of 10^7 times greater than this. For this reason, sensors which respond to the rate of change of the field are used, and the detector outputs are dX/dt , dY/dt and dZ/dt . Because of the low-pass RC circuit, which acts as an integrator, however, the quantities actually recorded are approximately X, Y, Z in the frequency range 1 to 50 cps. If the overall response were exactly flat, and if the phase shift were proportional to frequency, the result would be the same as measuring X, Y, and Z directly and then filtering out the lower and higher frequencies.

Data are recorded in three tracks on 1/4 inch magnetic tape at a speed of 0.3 inch/second. For the normal program of 15 minutes of each hour, a 2400 foot reel of tape records four days of data.

* 1 gamma (γ) = 1×10^{-5} oersted

1 milligamma (m γ) = 1×10^{-3} gamma = 1×10^{-8} oersted

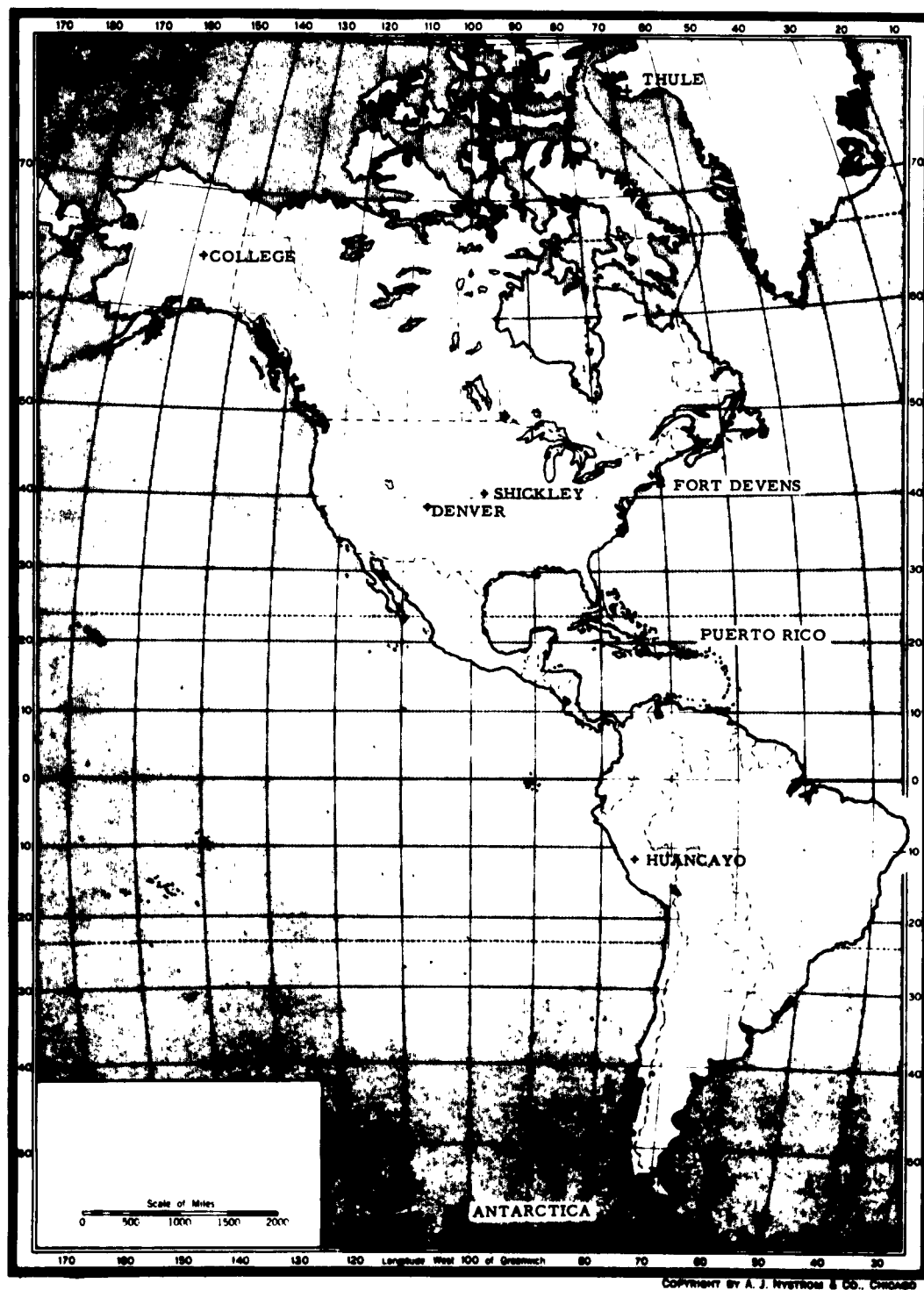


Figure 1. Locations of Recording Stations

Occasionally, for special purposes, recording is continuous. Calibration of the system is accomplished by reference to a standard field.

Reduction of the data to digital form is accomplished by a semi-automatic system. The tape speed used is 100 times that used in recording, or 30 ips. so that frequencies in the reduction equipment are 100 times the actual frequencies recorded, permitting faster processing and simpler equipment. The system filters the signal representing the field component and integrates these values over each 15 minute recording period (9 seconds integrating time at playback). The values thus obtained are taken as a general measure of the magnetic activity of a particular component for the hour in question within a particular octave frequency band. Further reduction to magnetic field units, is accomplished by an electronic computer utilizing calibration factors derived from the calibration signals on the tapes. This program results in a 24 hour printout having 18 values for each hour corresponding to the 6 octave bands in each channel. Another computer program produces a monthly summary for days and hours of the data obtained from a particular field component within a particular frequency band.

A large amount of data has been accumulated, and a good start has been made on its reduction and analysis. Most of the fluctuations in the 1 to 50 cps range originate in thunderstorm activity, and the records have yielded valuable information on propagation conditions in this range, including the resonance modes in the earth-ionosphere cavity. Recently, emphasis has been placed on data which could be studied for correlation of the 1 to 2 cps signal levels with meteor activity.

A. Planning

The initial steps toward generating an IGY program at DRI for study of fluctuations of the earth's magnetic field were taken by Dr. A. R. Jordan of DRI. He was in contact with Dr. Holzer of the University of California as early as October 1955. In the course of the next year, he had extended his correspondence and conferences to include Mr. Elwood Maple of the Geophysics Research Directorate, Sir Charles Wright of the Pacific Naval Laboratory, and E. B. Roberts, Secretary of the IGY Geomagnetism Technical Panel.

By October 1956, Dr. Jordan and Mr. Maple had arranged to work together, with the DRI effort to be funded via Air Force Cambridge Research Center under the cognizance of Mr. Maple.

A proposal, based on "Plan for Studying the Variations in the Geomagnetic Field" by L. R. Alldredge and E. Maple, was submitted 13 April 1956 by Dr. Jordan to the Geomagnetism Panel of the U. S. National Committee for IGY. Another proposal was submitted by Dr. Jordan, then Head of the Physics Division, to the Air Force Cambridge Research Center, and was accepted. A contract was awarded as of 6 December 1956 to run not later than 30 June 1959.

The statement of work was as follows:

1. "Investigate the natural fluctuations of the earth's magnetic field in the frequency range from one to fifty c/s during the IGY. This will include the provision of specialized instrumentation for five field measurement stations and a central analysis station."
2. "Operate three (3) field stations and the central analysis station which will process the records from the field stations."

As the expiration date for the contract neared, it became evident that the work could not be completed on schedule. A supplemental agreement was entered into between DRI and AF Cambridge Research Center effective 1 October 1959. A note was added to item 2 above as follows:

"One of the field stations will be located at College, Alaska, another at Huancayo, Peru, and the third at Mt. Evans, Colorado."

The following further stipulations were made:

3. That DRI was to "obtain a sufficient quantity of magnetic tape recordings at each field station to constitute a representative sample of the geomagnetic fluctuations for the data analysis program".
4. That DRI was to reduce the tape recordings obtained to "tables of average signal level vs. time in six frequency bands covering the one to fifty cps range, complete the preliminary statistical analysis of the tabular data to determine the general characteristics of the fluctuations, such as diurnal and seasonal variations of the signal levels at each station. Similarly reduce and analyze field station recordings supplied by the Geophysics Research Directorate from its field stations at Fort Devens, Massachusetts, and Thule, Greenland".

5. That DRI was to "Initiate theoretical studies and additional data analyses, such as correlation with other geophysical phenomena, in order to clarify the nature and origins of the geomagnetic fluctuations".

Under the most recent supplemental agreement, whose effective dates were 20 September 1960 to 30 September 1961, the following items were added under the statement of work:

6. "Perform suitable measurements of meteor trail reflections of radio transmissions for comparison with concurrent measurements of geomagnetic fluctuations attributed to meteor shower effects in the ionosphere."
7. "Investigate the feasibility of using the analysis equipment developed under this contract for the reduction of existing magnetic tape recordings of geomagnetic fluctuations in the frequency range 0.01 to 4 cps."

The present contract came to a close 30 September 1961. The work is to be continued under a new contract.

B. Data Collection

At the time the contract was awarded, the objectives and boundaries of the work were fairly well defined. Five recording stations were planned, including the two which were to be operated by GRD. Immediate objectives were to build equipment at DRI for the recording stations, choose and acquire sites, arrange for operating personnel, and get the recording operation underway.

1. Recording Site Locations

To provide a wide coverage of possible variations in the type of magnetic fluctuations as well as in the amplitudes and propagation conditions of the signals received from the various thunderstorm centers of the world, station locations were selected to cover a wide range of latitudes. Practical considerations of logistics and availability of operators were also very important. There was particular interest in possible differences between the auroral zone stations and those at lower latitudes. Of the original five stations, the one at Alaska is near the maximum of the northern auroral zone, Thule is near the center of the northern auroral zone, Ft. Devens and Denver are at

middle latitudes, while Puerto Rico is at a lower latitude. Later, Huancayo was selected as a replacement for Puerto Rico, and Shickley, Nebraska, was chosen because of its relationship to the meteor-propagation data of the NBS Central Radio Propagation Laboratory. It is hoped that an Antarctic station in the southern auroral zone will go into operation early in 1962.

The Puerto Rico station was located at the northwest corner of the island, practically on the shore, at approximate latitude 18.5°N , longitude 67.2°W . It was thus nearly at sea level, and in a relatively hot and humid environment.

The Thule station was established at Thule Air Force Base on the northwest coast of Greenland, near the north geomagnetic pole (i. e., axis of best-fit central dipole). Approximate coordinates are 77°N , 73°W , placing it in an area of polar climate and high winds. It is approximately 600 miles east of, and possibly 300 miles north of, the north magnetic pole. Because of this unique location, the sensors were oriented to magnetic compass directions rather than geographically.

The Fort Devens station was approximately 25 miles inland from the seacoast, northwest of Boston, Mass. Its approximate coordinates are 42.5°N , 71.5°W . It is in a temperate climate, and at an elevation close to sea level.

The Alaska station, like Thule, was located in a polar climate and in the auroral zone, but inland, about 250 miles from the nearest seacoast. The actual recording site was some 25 miles southwest of College, Alaska, which is near Fairbanks. Approximate coordinates of the recording site are 65°N , 148°W .

The Denver station was located in an alpine climate on the slopes of Mt. Evans, about 45 miles west of Denver, and at an altitude of 10,000 feet. Approximate coordinates are 39.7°N , 105.7°W . There are seasonal winds at this site with gusts to 55 mph in Spring and Autumn.

The Huancayo station in Peru is 120 miles east of Lima, and is close to the geomagnetic equator at 14°S , 75.5°W . It is located at approximately the same elevation as the Denver Station.

The Shickley station is located just north of the town of Shickley, Nebraska, at coordinates 40.5°N, 97.7°W. It is at the eastern edge of the high-plains area at an altitude of 1500 feet. It has a continental climate.

The Antarctic station is to be located at Byrd Satellite 1 station which is about 40 kilometers from the main Byrd Station, whose coordinates are 78°11'S, 162°10'W.

2. Development of Instrumentation

The present instrumentation is described in detail in later sections of this report. The fundamental design of the equipment is essentially that conceived in the opening stages of the contract, but as would be expected in the development of completely new instrumentation where it is necessary to utilize to the limit the current state of the art in order to obtain the necessary sensitivity and operating characteristics, many difficulties and unexpected problems were encountered. It would have been highly desirable to construct and thoroughly field test one set of recording equipment before a determination on the design for all the field stations was made. However, the contract began only six months before the start of the IGY, and since a number of special components had to be selected and procured, it was deemed necessary to make many decisions on the design at an early date. The situation was further complicated by the fact that as of 1 September 1957, under a general Department of Defense policy, the rate of expenditure under the contract was severely restricted. Notification of the removal of this restriction was received on 20 November 1957. Late delivery of some components, including the Ampex magnetic tape transports, also contributed to the delays.

The field tests revealed that the signal-to-noise ratio was unsatisfactory, partly due to faults in the equipment and partly due to somewhat lower signal levels than had been anticipated, particularly at the low-frequency end of the 1 to 50 cps band where the signal voltages developed in the sensor-coil are the smallest. Circuit modifications and substitutions of higher quality components improved the signal-to-noise ratio quite appreciably, so that it was quite satisfactory above about 4 cps but still poor at 1 cps. It was also discovered that the sensor coil-input transformer combination was resonant at about 35 cps, which cast doubt on the validity of the data. The resonance was due to the extra capacitance added by the 300-foot cables used at the field stations between the sensors and the amplifiers, and it became

necessary to redesign the sensor coils and to reduce the number of turns in order to raise the resonant frequency above 50 cps. Mr. Maple spent three weeks in Denver helping DRI personnel solve these problems.

The result of these difficulties was that it was in May 1958 that the first usable field recordings were obtained. At that point, the field recording equipment was capable of putting out useful data, although still with a poor signal-to-noise ratio at the lowest frequencies of interest. It was still far from ideal for field use, however, as it required considerable attention and care on the part of the operator for optimum performance. It was also difficult to service when trouble developed, partly because of the early, over-optimistic decision to use printed-circuit construction in the amplifiers; this construction was unsuited for later modifications which proved necessary.

It should be pointed out that the natural magnetic fluctuation levels result in signals of only a few microvolts at the first grid of the amplifier, while the signals in the sensor and input transformer primary are very small fractions of a microvolt at a frequency of 1 cps. Thus, there are very real difficulties in recording these small fluctuation levels with reasonably portable field equipment.

It was not for several months more that the remaining sources of instrument noise were adequately identified. These turned out to be chiefly of two types. One was thermo-electric emf's generated by changing temperatures or moving air currents at soldered connections in the input circuit; this trouble had not been anticipated at frequencies as high as 1 cps, but this type of noise turned out to be comparable to the very small voltages generated by the natural fluctuations. The second source of noise was "flicker effect" in the cathodes of the first two amplifier tubes caused by transients coming in on the ac power line. Even with voltage regulators in the ac line, these transients were large enough in the rectified and filtered, but unregulated, dc filament current which was used. The thermal noise could be greatly reduced by proper thermal shielding. Precisely regulated dc power supplies (expensive and slow in delivery) were needed to reduce the flicker noise to an acceptable level; batteries were used at one station but were not practical at most field stations. These measures were not completely in effect at most stations until well into 1959.

For the Antarctic station (not yet in operation) the amplifiers have been redesigned both electronically and mechanically, and new detector coils have been redesigned. It is believed that most of the

difficulties in the earlier equipment have been removed, but field experience with the new design is still lacking. A remaining weakness is the Ampex tape transport which is operated at 0.3 inch/second. At this speed, the tape flutter is such that the dynamic range available for the recorded signal is only about 27 db at best and may be less. This means that the gain of the system must be rather carefully selected if optimum results are to be obtained.

The playback and data reduction system was greatly delayed first by the restriction on contract expenditures which delayed the ordering of components and later by the fact that all available personnel were occupied during the first half of 1958 with getting the field station recording equipment into operating condition. It was not until February 1959 that the reduction equipment had progressed to the point that it could be used to check the operation of the recording stations. This was a considerable handicap in the operation of the field stations, which had no means of checking their own magnetic tapes.

The original design of the data reduction system was an ambitious one, and continuous, reliable operation of the system proved to be beyond the capabilities of the equipment components commercially available at the time. Thus, it has been necessary to improve various aspects of the operation many times during the course of the contract. It has developed to the point where the semi-automatic reduction of the tape recordings can be conducted on a fairly continuous and reliable basis, and a considerable amount of data have been reduced and used for analysis.

II. RECORDING SYSTEM

The overall function of the recording system is to sense three mutually perpendicular components of fluctuations of the geomagnetic field and to record the resulting data on magnetic tape for later study. The recording systems used at the various stations have had essentially similar characteristics.

A block diagram of the recording station is shown in Figure 2. The sensor system consists of three cylindrical coils approximately 2.5 feet long by 3 inches outside diameter. The three sensors are oriented to detect fluctuations of the three mutually perpendicular field components X(North), Y(East), Z(Vertical). Corresponding to the three components, the recording system has three channels, each consisting of sensor, connecting cable, amplifier, and a frequency modulated oscillator operating into one of three recording heads on a tape deck. The three channels of data are thus recorded in FM form on a single 1/4 inch tape at 0.3 ips. Identity of the individual field components is maintained throughout the recording and reduction process.

A. Sensors

The sensors for all three channels are the same, except in the Antarctic Station. Each consists of a 4-layer coil of 1000 turns of #16 wire wound in the form of a solenoid 30 inches long with outside and inside diameters of 3 and 1 inches, respectively.

Figure 3 is a diagram of one of these sensors. In use, a core of mu-metal is inserted in the solenoid to increase its sensitivity. The cores used are 58 inches long by 13/16 inches diameter. Although the true permeability of mu-metal is approximately 20,000, it is possible only to realize an effective permeability of approximately 1000 due to the demagnetization effect in rods.¹

A mounting, which is essentially a rigid box of 3/4-inch plywood with legs of 4 x 4 lumber, is used to maintain the sensors in the mutually perpendicular orientation. When the sensor system is installed at a site, it is aligned within a degree of true north, and is carefully levelled for vertical alignment. A shelter is erected around the mounted sensors to protect them from wind and weather. Only non-magnetic fastenings (brass or aluminum) are used throughout both the mount and shelter.

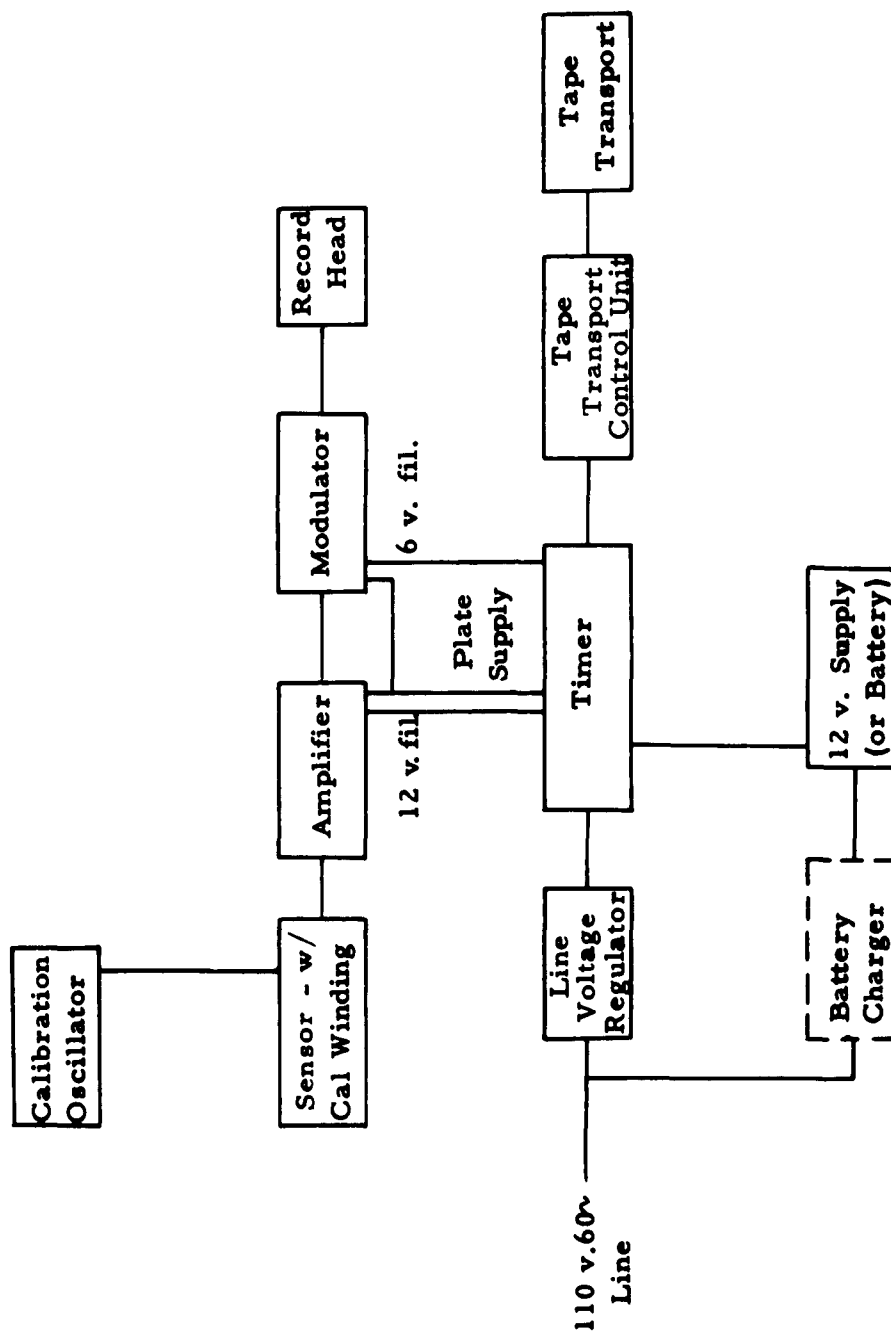


Figure 2. Block Diagram of Recording System

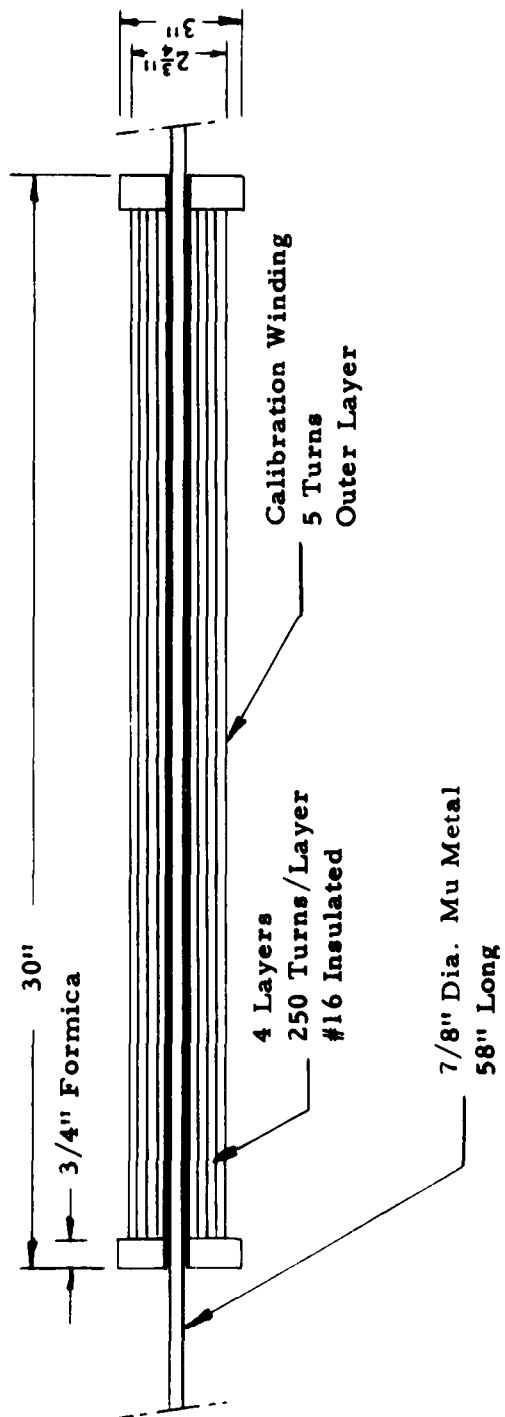


Figure 3. Typical Sensor Coil

A calibration winding of a few turns is wound over the main winding at the center of the sensor coil to provide a convenient means of calibration. The 1000-turn coils were adjusted to have a calibration constant of 7.25 γ /ma, i. e., a current of 1 ma rms produces the same output at the coil terminals as a uniform field of 7.25 γ rms. Double-shielded cables are used to connect the sensors and calibration coils to the amplifying and recording equipment.

In the Antarctic Station, two different types of sensors will be used. For the horizontal components, an improved version of the coil/core sensor was constructed, and a large loop laid on the surface of the ground is to be used for the vertical component.

The new coil sensor is pie-wound in a number of sections to reduce its self-capacitance; a larger number of turns than on the older sensors may thus be used without reducing the resonant frequency of the sensor-cable-input transformer combination below 50 cps. It is composed of two sections, each consisting of 1250 turns of #12 plastic insulated wire wound in 5 parts of 250 turns each. The two sections are mounted together and are joined magnetically by a mu-metal core of the same dimensions as used previously.

The full performance of these sensors has not been measured in the recording system since their construction and calibration was completed just in time for them to be shipped, and no further time was available. A photograph of one of these units is shown in Figure 4; a schematic in Figure 5.

B. Amplifiers

Output of the sensors is coupled to the amplifiers by means of a transformer having selected low-frequency characteristics. The amplifiers are of more or less conventional design using the principle of dynamic plate loading. This type of circuit is well suited for a high-gain amplifier (about 10^6 at 1 cps), since it provides very effective rejection of small variations of B+ voltage and eliminates the need for decoupling filters for the separate stages. At these low frequencies, the gain of each stage is approximately equal to the amplification factor of the tube; at higher frequencies the gain would be reduced by capacitance effects.

A low-pass RC network is used between the first and second stages so that the response decreases with increasing frequency. The sensor, being basically an inductive device, actually develops an output



Figure 4. Photograph of Antarctic Type Sensor Coil

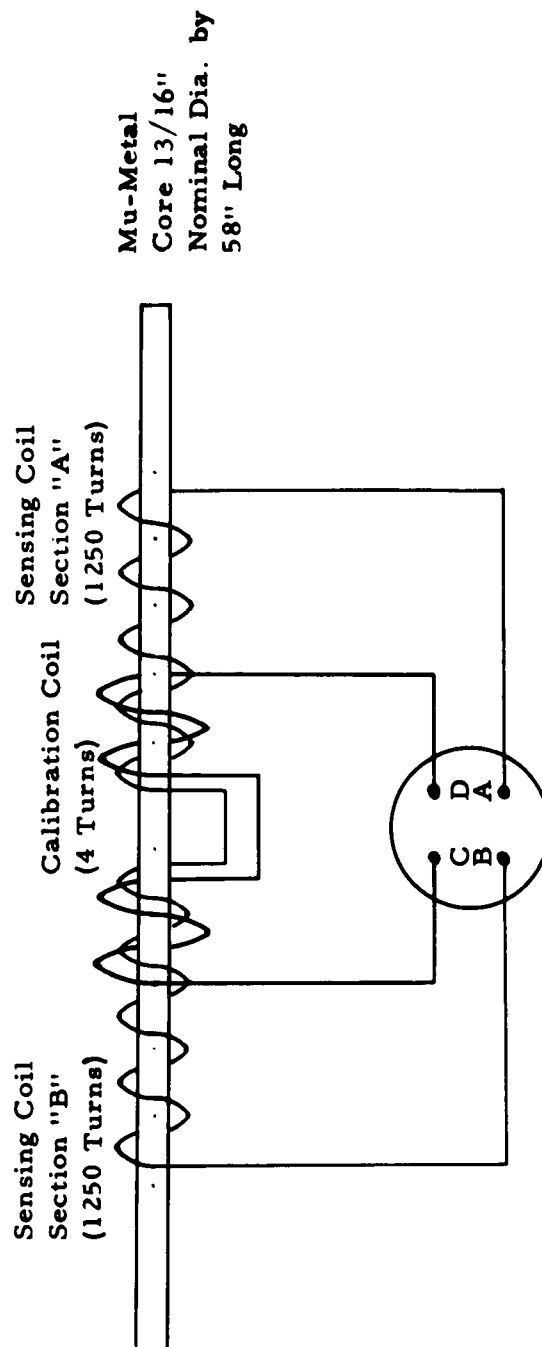


Figure 5. Schematic of Antarctic Type Sensor Coil

signal which is proportional to dX/dt , dY/dt , or dZ/dt , the time derivatives of the three components of the earth's field. Thus its output increases with frequency for a constant amplitude of field variation. It is for this reason that the RC network is incorporated in the amplifier, largely compensating for the response of the sensor, and resulting in more or less constant overall response of the sensor-amplifier combination over the frequency range. Flat frequency response is not absolutely essential, since response can be corrected for in the calibration procedures. It is certainly highly desirable, however, since it would greatly simplify the later handling of the data; it would also simplify the field calibration procedures. Also, as noted earlier, a flat overall response means that the output is proportional to H rather than to dH/dt .

A schematic of the type of amplifier used at all the recording stations except the Antarctic is shown in Figure 6. An additional low-pass filter is used after the second stage as shown to confine the response of the amplifier within the 1 to 50 cps range, and especially to minimize interference and noise at 60 cps and related frequencies.

Amplifiers incorporating an additional stage are to be used for the Antarctic station as shown in Figure 7. These amplifiers were adapted from a design by Charles B. Sawyer which was developed by him at the Thule station. Its first two stages constitute a low-level preamplifier utilizing negative feedback; the purpose is to reduce the circuit noise contributed by the first amplifier tube (principally "flicker noise") and to present a very high stable impedance (greater than 100 megohms) to the input transformer. This impedance characteristic is necessary if the transformer gain is to be high and constant at the upper frequencies near 50 cps. In the older circuit this gain varied somewhat with the condition and age of the first tube. The feedback used also reduces the effective gain of the first two tubes, so that an additional tube is required in this design. The remainder of this circuit is similar to the earlier circuit.

C. Frequency-Modulated Oscillators

Ideally, at the output of the amplifier, the signal is an analog of the applied field within the restricted frequency range. It is not an exact analog because of the differentiating action of the sensor and the integrating and filter networks in the circuit. This analog signal is used as the control voltage for an oscillator whose output frequency is a linear function of input voltage over its operating range. A typical frequency vs. control voltage plot is shown in Figure 8.

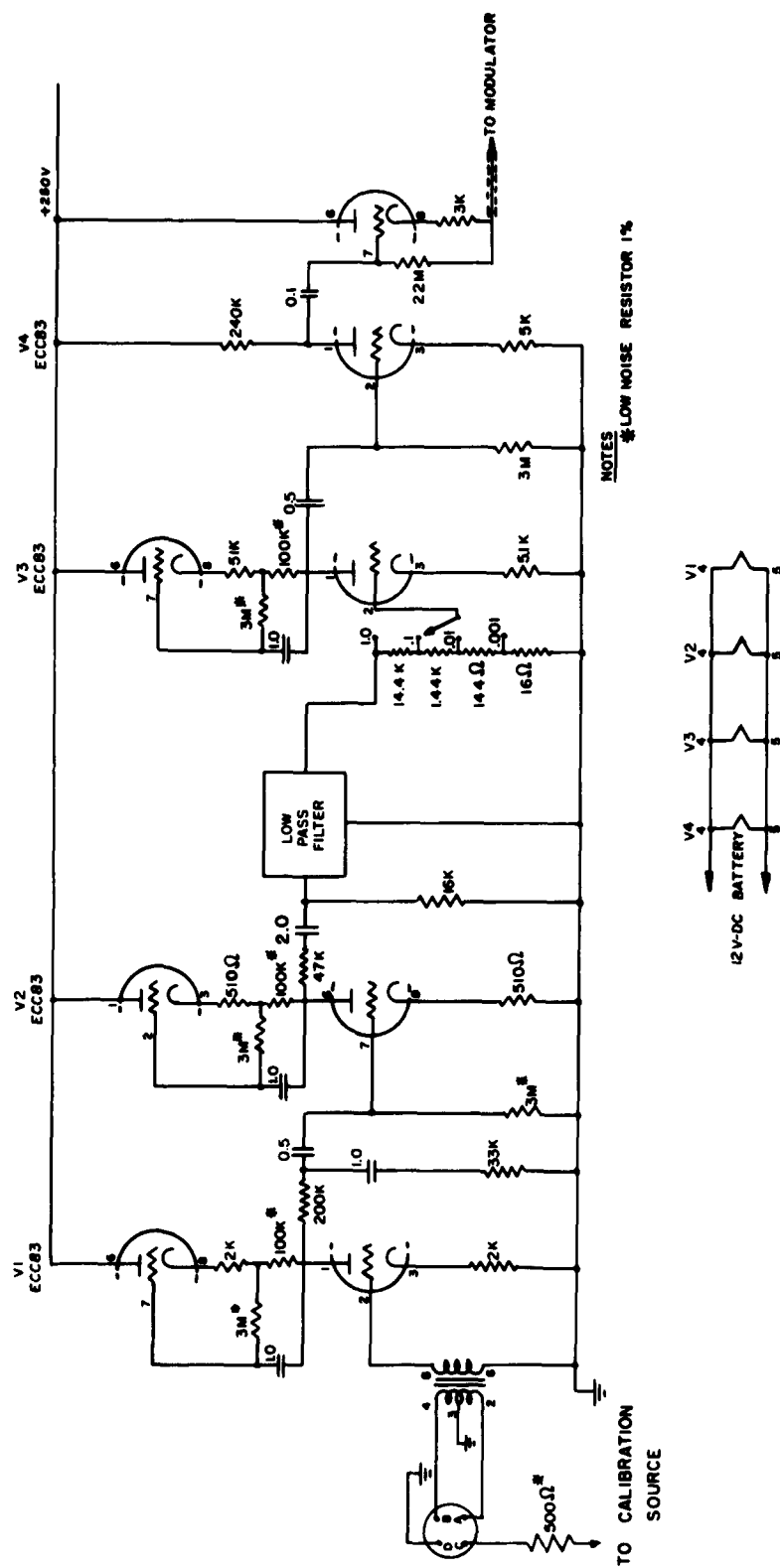


Figure 6. Schematic of Recording System Amplifiers

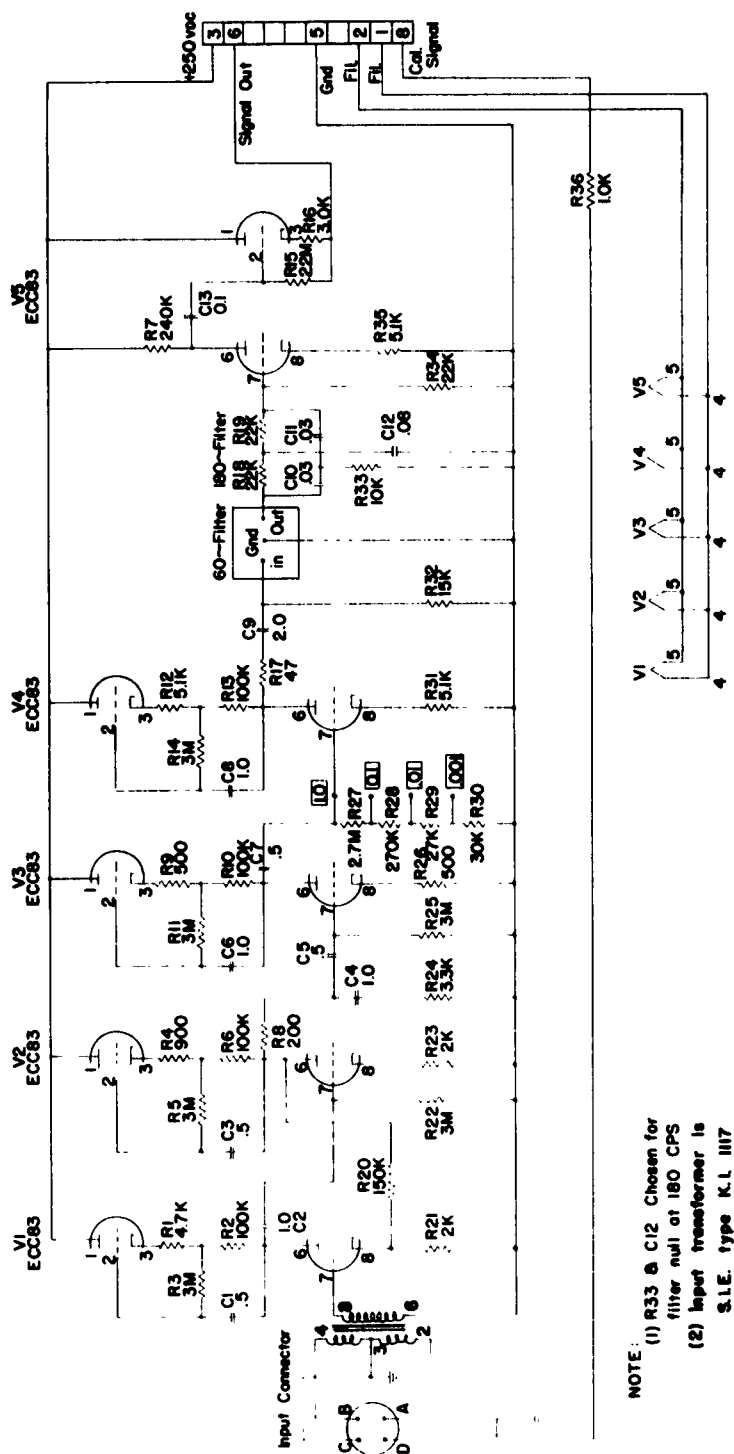


Figure 7. Low Noise Recording Amplifier for Antarctic Station

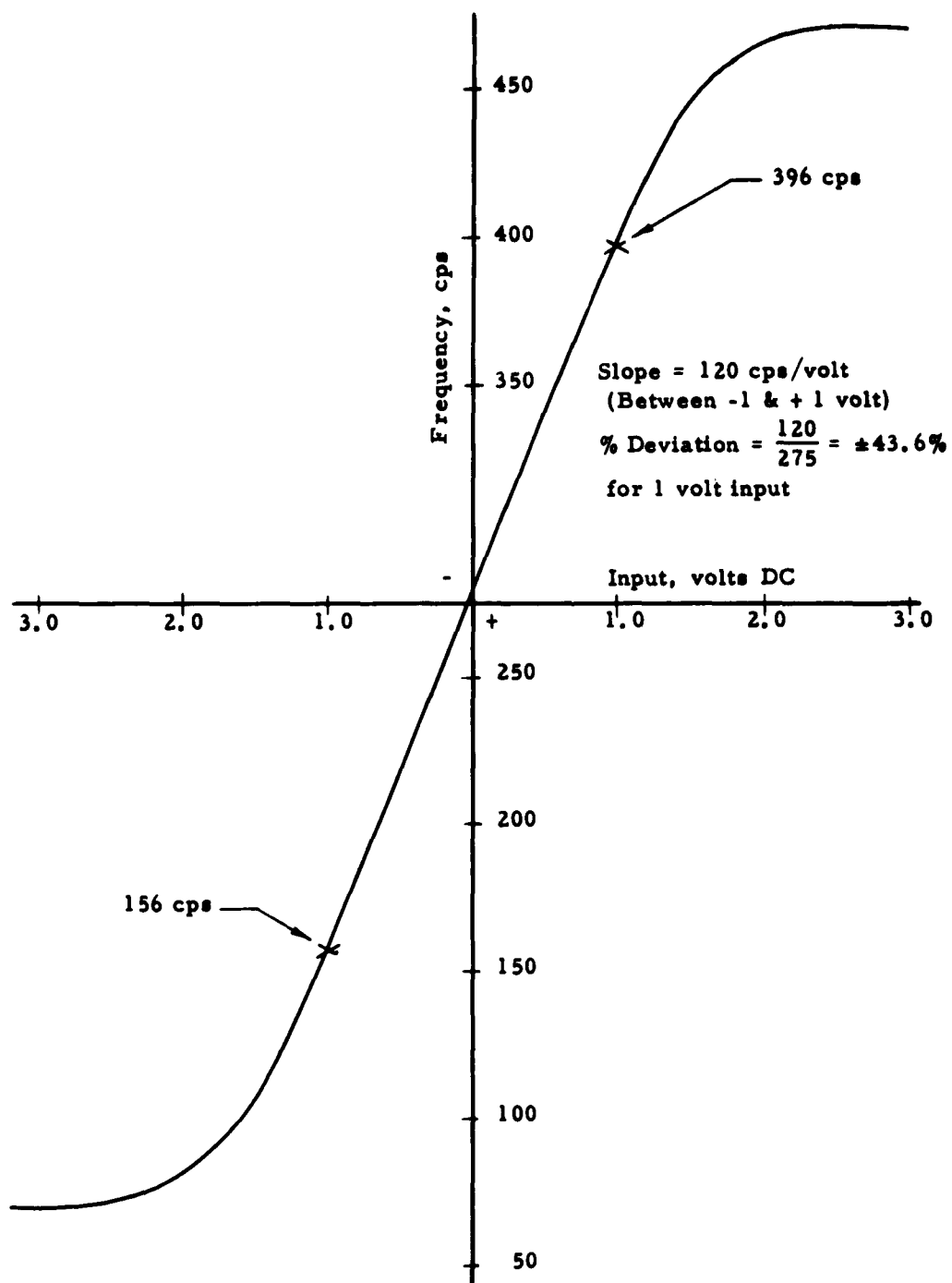


Figure 8. Characteristic of Frequency-Modulated Oscillator: Output Frequency vs. Control Voltage

The FMO (frequency modulated oscillator) as this unit is called, consists basically of a 6AS6 tube connected as a free-running phantastron operating at 275 cps, together with input and output stages for coupling to the amplifier and the recording heads, respectively. A schematic is shown in Figure 9.

In use, the FMO is adjusted and checked for proper operation by the following procedure: after the voltage at test point 1 is adjusted to 110 volts DC, output frequency is adjusted to 275 cps by comparison with the calibration oscillator. Readjustments are made until both voltage and frequency remain at the required settings. The presence of the signal at the tape heads is verified by observation of the waveform at test point 2. Since the tape heads form part of this test circuit, presence of the proper waveform at this point indicates that the signal is reaching the recording heads.

The output from the FMO to the tape heads is a rectangular wave whose repetition frequency is proportional to the modulating or control voltage from the amplifier. When this is recorded on, and played back from, a tape running at constant speed, the demodulated signal is essentially a replica of the control voltage.

The frequency-modulation method of recording was chosen because it is less subject to aging problems and other factors affecting the signal level than analog recording. In this method of recording, the magnetic material of the tape is saturated in opposite directions by the signal on each successive half-cycle of signal. The information content is contained purely in the frequency variations rather than in the degree of magnetization of the tape and is independent to a great extent of signal level on the tape.

D. Tape Recorder

The recorder used is an Ampex Series 1100 modified to operate only at 0.3 inches per second. At this low tape speed, and at the low signal frequencies, tape flutter with this transport is appreciably greater than at higher tape speeds and signal frequencies. As a result the tape flutter is only about 27 db down on full modulation of the FM carrier, and the dynamic range available for the wanted signal is correspondingly reduced.

The tape deck is mounted in a carrying case, as is also its control chassis. The tape heads are spaced and mounted so as to produce three tracks on 1/4 inch tape. Track width is .050 inch,

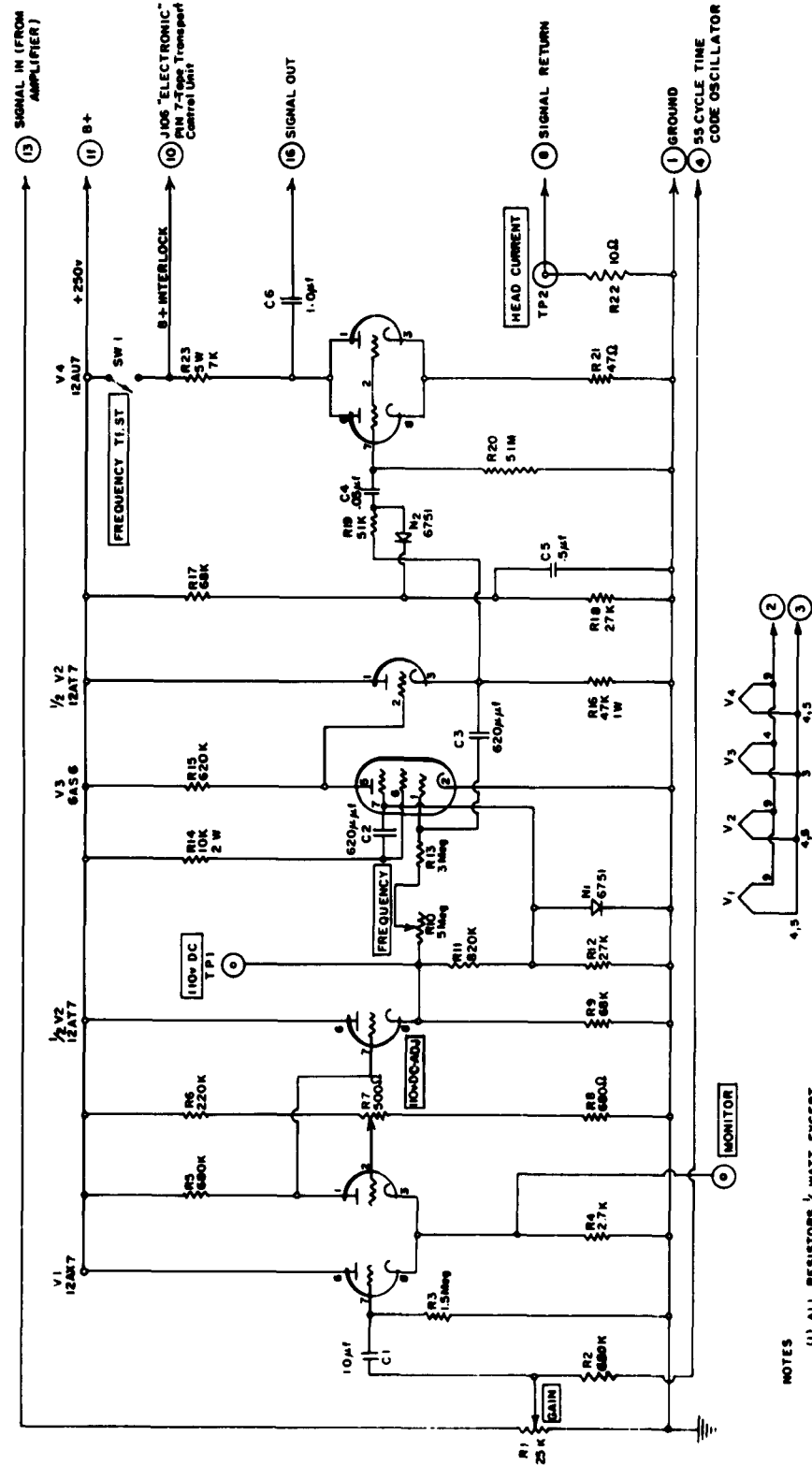


Figure 9. Schematic of Frequency Modulated Oscillator

and center-to-center distance between tracks is 0.70 inch. The type of tape used for the majority of our data recordings has been 1/4 inch wide 1 1/2 mil polyester, 2400 feet to the roll (Minnesota Mining and Manufacturing Type 102-24R). At the normal recording speed of 0.3 ips, and the normal duty cycle of 25%, i. e., 15 minutes of recording out of each hour, one tape lasts approximately four days. Continuous recording has been used in some cases, resulting in usage of one tape per day.

E. Calibration

Calibration of the tape recordings in the field is accomplished by means of the calibration coil wound over the main coil of the sensor. The amplifier gain is first reduced by a factor of 100 by means of a step attenuator so that the amplifier output due to the natural field variations at the sensor is negligible. A measured current of known frequency is then passed through the calibration coil to produce an output voltage comparable to that of the natural signal level at the normal attenuator setting, and this output is recorded on the tape for the standard 15 minute interval. When the tapes are played back, these calibrations establish the overall sensitivity of the recording and playback equipment in terms of known magnetic field variations at the sensors and may thus be used to assign numerical values in magnetic field units to the data output. For example, if the calibration coil constant is 7.25 gammas/milliamper and a 0.1 milliamper calibration current at 5 cps is used, the output at playback is the same as would have been produced by a uniform 5 cps sinusoidal magnetic field of 7.25 milligammas at the sensor with the recording amplifier at its normal gain setting.

The basic constant of the calibration coil is determined at the time it is wound on the sensor by the following procedure: the sensor is placed in a known uniform magnetic field produced by a "cube-surface coil".² The field is sinusoidal and selected frequencies are used. The voltage developed by the sensor coil working into its associated amplifier is measured. Then the current in the calibration coil which is required to produce the same output is measured. From this data a calibration constant can be determined.

The sensor coils used at all stations preceding the Antarctic station have calibration constants very close to 7.25 gamma/milliamper, i. e., a current of 1.0 ma rms in the calibration coil produces the same voltage at the sensor system output as a varying magnetic

field of 7.25 gamma rms. The calibration constant of the Antarctic type sensors was 5.42 gamma/milliampere.

The cube coil used had dimensions 60 by 60 by 60 inches. All five windings were in series. The center winding had 10 turns, the end windings had 19 turns each and those midway between had 4 turns each. The axial distance between adjacent windings was 15 inches. Reference 2 gives the field at the center of this system of coils as $\frac{35.69 \text{ oersteds}}{d \text{ ampere}}$, where "d" is the length of one side in cm. For the coil used this is equivalent to 23.4 gamma/ma.

Since the core of the sensor was nearly as long as the cube coil within which it was placed, and since the field produced is appreciably smaller at the ends of the coil system than at the center, there is a possible error in this method of calibration aside from errors of electrical measurement. From the field distribution given in Reference 2, the average field applied over the 58" length of the sensor core is less than 1% lower than the value at the center. The systematic error introduced is thus quite small.

F. Timing System

The timing unit automatically controls the recording operation by switching supply voltages to the amplifiers, modulators, and tape transport. It also provides an indication of present time on the front panel meter. Provision is made for disabling or bypassing the switching functions to set the correct time initially, and to permit other system adjustments.

A block diagram of the timing system is shown in Figure 10 and schematics of its functional units in Figures 11 through 14. The timing unit consists of a 1.0 rpm synchronous timing motor, a cam-operated switch driven by the timing motor, and a bank of four stepping relays cascaded in a counting configuration. Pulses from the switch at the rate of one per minute drive the stepper. Thus line frequency provides the time base for the automatic recording operation. Provision is made for manual resetting of the timing circuits to the correct time so there is no long-period accumulation of error. A time-signal oscillator and a panel meter for display of time are also incorporated. The purpose of the oscillator is to provide a 55 cps signal which is recorded momentarily on the tape in a coded pattern at the start of each recording interval to provide an unambiguous real time identification.

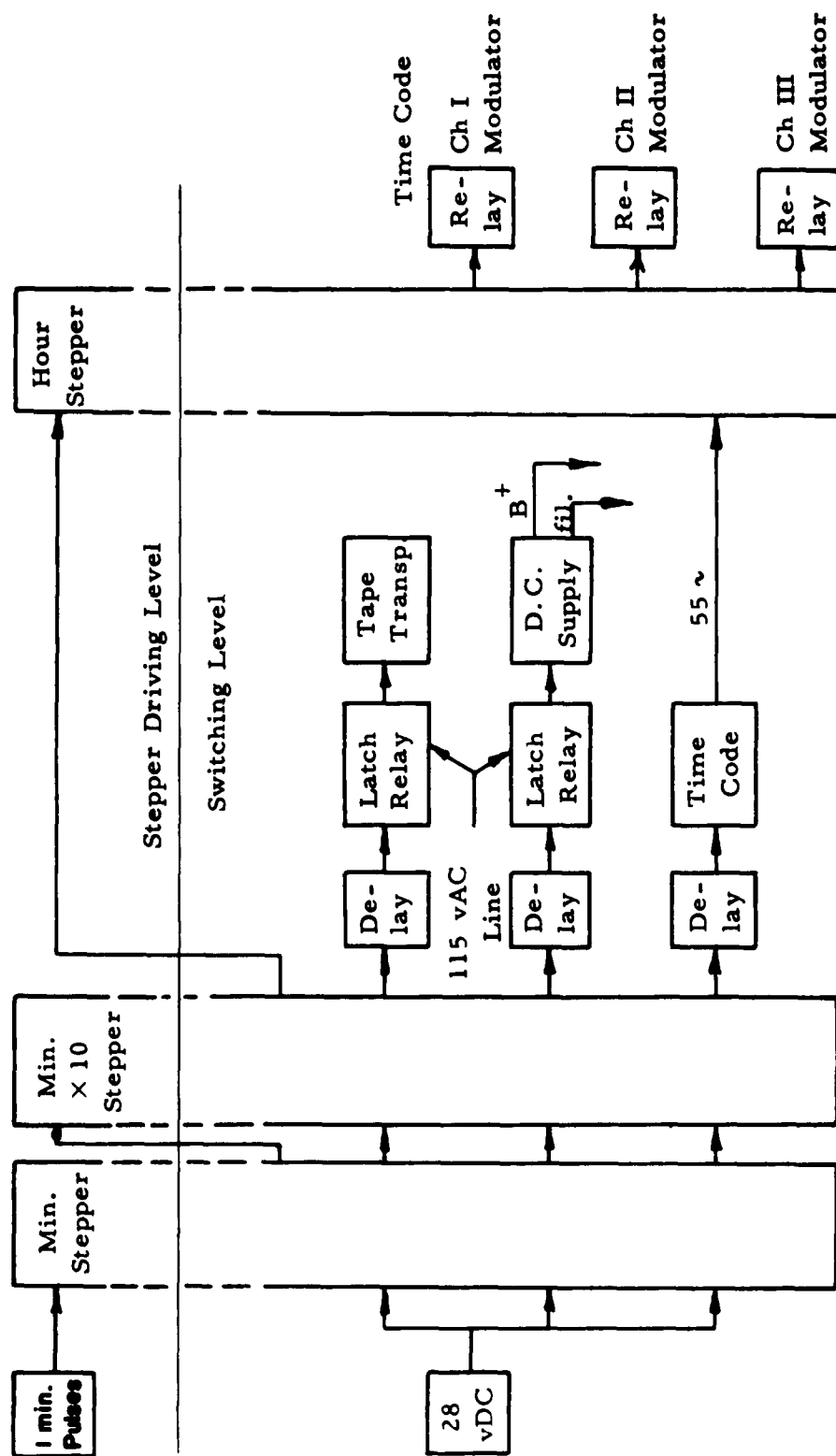


Figure 10. Block Diagram of Recording System Timer

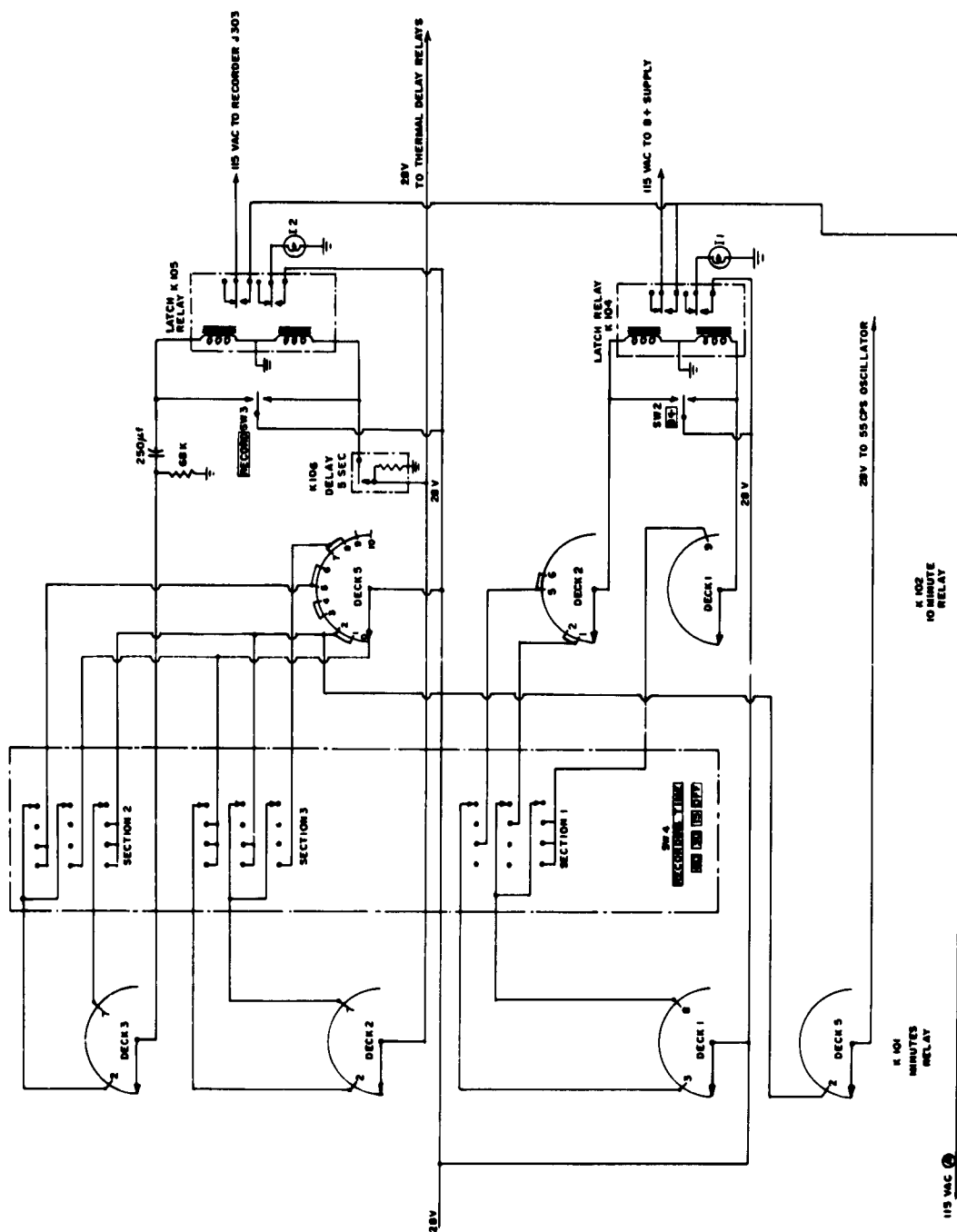


Figure 11. Power Switching Circuits in Timer

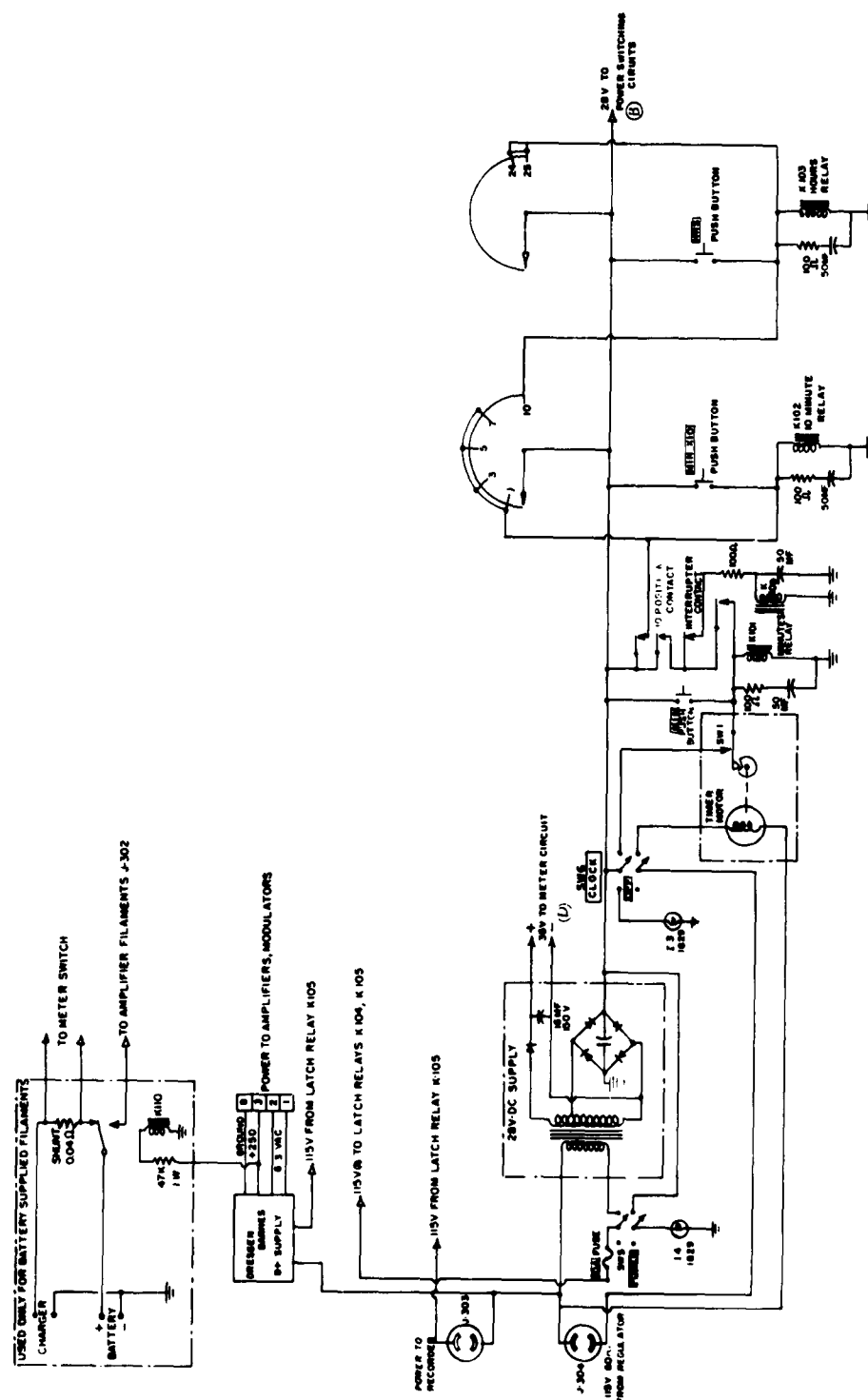
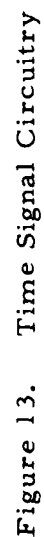


Figure 12. Stepping Relay Circuitry



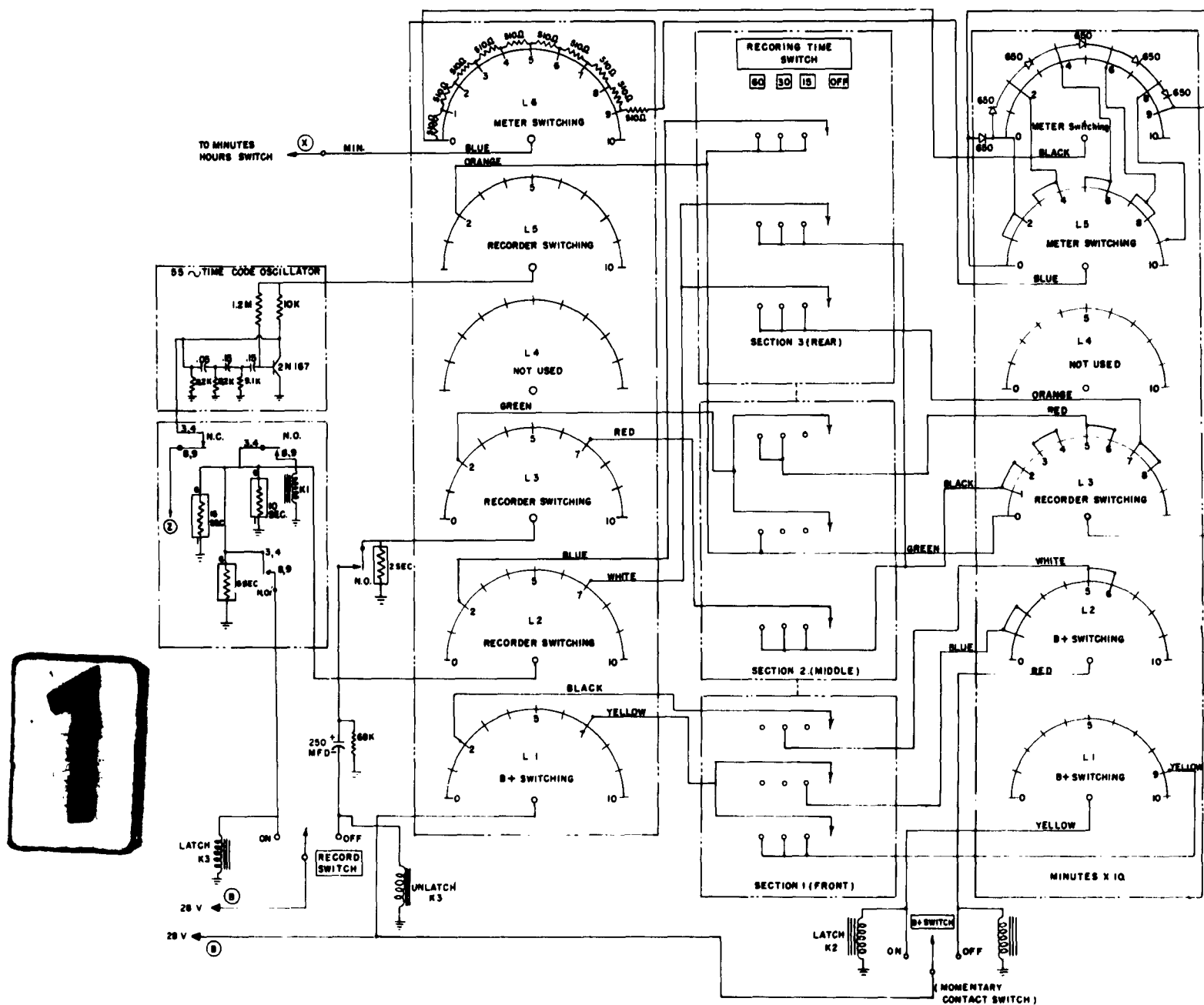


Figure 14. Recording Timer Switching System (Overall Scheme)

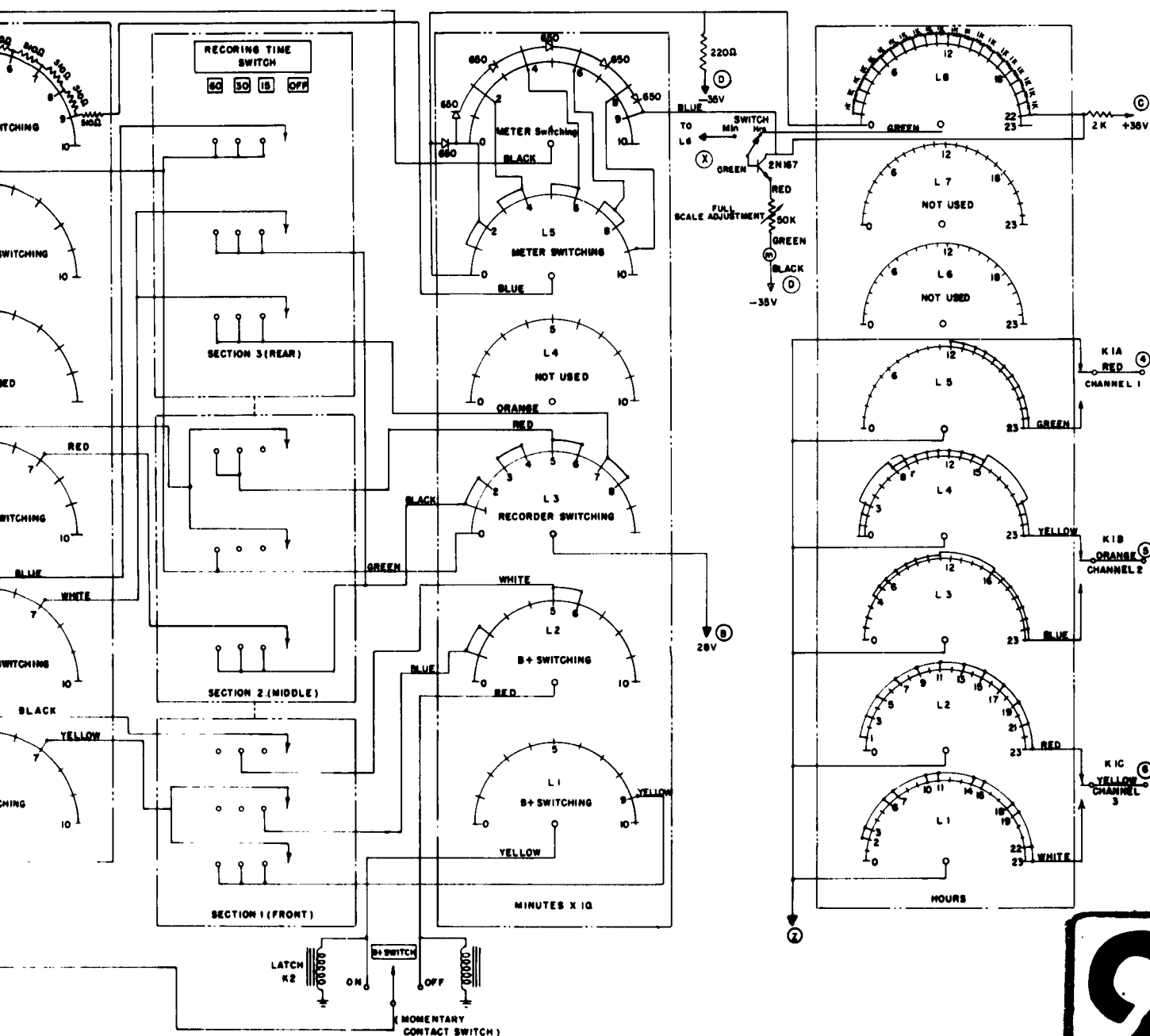


Figure 14. Recording Timer Switching System (Overall Schematic)

2

The stepping relays count minutes, tens of minutes, and hours. All relays are at their zero position at 0000 hours of each day. The "minutes" relay steps one position per minute from 1 through 9, then skips the 10 position and returns to zero. The "minutes $\times 10$ " relay steps once each 10 minutes, going to positions 2, 4, 6, 8 and 9 in sequence and then returns to zero, skipping the intermediate positions because of bypass circuits. The "hours" relay steps one position per hour through the 23rd hour and then returns to zero.

Pulses from the cam-operated switch may be disabled by the "Relays" switch, at which time the relays may be operated by front panel push-buttons for manually setting the timer to the nearest minute. The clock motor may be shut off by means of the timing motor switch and then restarted at the appropriate instant so that the timer is set to within a second of the correct time.

Level 1 on the "Minutes" relay, and levels 1 and 2 on the "minutes $\times 10$ " relay, control the switching of line power to the B+ supply. These connections provide a 110 volt return beginning 2 minutes before the hour and lasting through 17 minutes after the hour. The "B+" switch bypasses these decks so that power may be applied at any other time manually. The "Record Time" switch will disable the timing unit function as desired.

Levels 2, 3 and 5 on the "Minutes" relay, and level 3 on the "minutes $\times 10$ " relay, control line power to the tape transport, completing the circuit at 2 minutes after the hour, and maintaining it until 17 minutes after the hour. Thus the recording period begins after a four minute warm-up. The "Record" switch bypasses these decks for manual operation.

Panel indication of the time is provided by voltages from the time signal oscillator. The position of each stepping switch controls a step attenuator, which adjusts the time signal oscillator voltage to a value on the panel meter indicating the relay position. Setting the selector switch successively to "HR $\times 10$ ", "HR $\times 1$ ", "MIN $\times 10$ " and "MIN $\times 1$ " gives the four digits of military time, 0000 to 2359. The time signal oscillator itself is a 55 cps phase shift oscillator, powered by 30 VDC from a selenium rectifier circuit. The meter signal is amplified by an emitter-follower.

Initially it was planned that the time oscillator signal would be the basis for timing the reduction process, especially for establishing the correspondence between particular data values and real

time. However, the presence of the "carrier break" on the tape between successive periods of recording has served this purpose sufficiently well most of the time. Occasionally though, reference to the coded time signal is necessary, so it has been retained in all versions of the recording system which have been constructed.

The carrier break is merely the absence on the tape of any signal for a short period of time. It is produced when the recording period is ended by coasting of the tape drive after its power has been turned off. At the low tape speed involved, 0.3 ips, there is very little coasting, however, and the carrier break is so short in some cases as to make operation of the reduction system marginal. To eliminate this possible cause of error, the system most recently constructed (Shickely, Nebraska) incorporated a delay relay and auxiliary circuitry to provide a timed uniform carrier break of at least 2 seconds, equivalent to 0.6 inch space on the tape.

G. Auxiliary Equipment

1. Power Supplies

The recording system is designed to work on 117 VAC 60 cps single phase power. Normally, an AC regulator is used between the line and the system to minimize power supply variation problems. Plate supply power at 250 volts D.C. is provided for the entire system by a Dressen-Barnes modular regulated supply, Model 4-200X, which is physically located on the timer chassis. It also provides heater power at 6.3 volts to the modulator chassis. Heater power for the amplifiers is provided at some stations by a regulated 12.6 volt supply, or at other stations by a 12-volt automotive type storage battery which is charged only when it is not being used to provide filament power for the amplifiers. In normal operation, the amplifiers and the rest of the system are in operation only 15 minutes of each hour, and the battery charge is kept up by low-rate charging during the remaining 45 minutes of each hour. The charger is turned off during recording periods to minimize the possibility of line-frequency being introduced into the low-level amplifier stages.

One other supply is required to provide 26 volts D.C. for operation of the stepping relays and transistor circuitry of the timer unit. It is also a modular supply manufactured by Dressen-Barnes, and is located on the timer chassis.

2. Calibration Oscillator

Three different types of calibration oscillators have been used at different times and at different stations. They are the Krohn-Hite push button oscillator Model 440-A, the Hewlett-Packard Function Generator Model 202C, and the Hewlett-Packard Oscillator Model 202-CD. The latter was used at the Thule station and was later sent to the Antarctic station. The K-H oscillators have been used at the Alaska and Huancayo stations, and the HP Function Generator is in use at the Shickley station, having previously been used at the Denver station.

3. Calibration Meters

Ballantine A. C. voltmeters have been used as the calibration standard in all cases. A battery-operated type was in use at the Denver station, and is now in use at Schickley. Other stations have had an A. C. -powered version of the same meter. The battery type is Model 302, and the A. C. type is Model 310A. Their rated accuracy is 3%.

4. Wind Recorders

It was recognized that the presence of high wind conditions might become a source of serious error, due to coupling of motion into the housing and support structure of the sensors. The micro-pulsations to be recorded are of very small magnitude, and even slight motion of the sensors in the much greater static field can generate signals exceeding those caused by the natural fluctuations of the field. Sensor mounts and housings were designed to avoid, as far as possible, this source of spurious signals. Nonetheless, it was found, especially at Denver and Thule, that there was a definite effect of this sort. To provide a basis for eliminating data taken under high wind conditions, wind recorders were used at these stations. They were Bendix Aerovane systems with Esterline-Angus recorders. No attempt was made to record wind direction, merely magnitude. It is probably not possible to correct for the effect of wind, but at least data taken under high wind conditions can be eliminated from consideration.

5. Edin Recorder

The Thule station was equipped with a recorder system made by the Edin Co. It is a pen-recording system, and was intended to

be used for recording the total signal from one sensor, primarily for the purpose of identifying periods of high activity in the low frequency range below and overlapping the frequency range of the recording system. This recorder was shipped for further use to the Antarctic station.

6. Integrated-Activity Recorder System

For the purpose of monitoring the overall activity level as evidenced by the output of the sensors, an integrating amplifier circuit of very long time constant was developed at the Thule station.

Its input is taken from the monitor point on one of the channel amplifiers. It drives an Esterline-Angus recorder with chart speed of 6 inches per hour. In this way, a visual record of overall activity is produced on a relatively short length of chart. The circuit is shown in Figure 15. A unit for the Antarctic station was constructed following this same circuit.

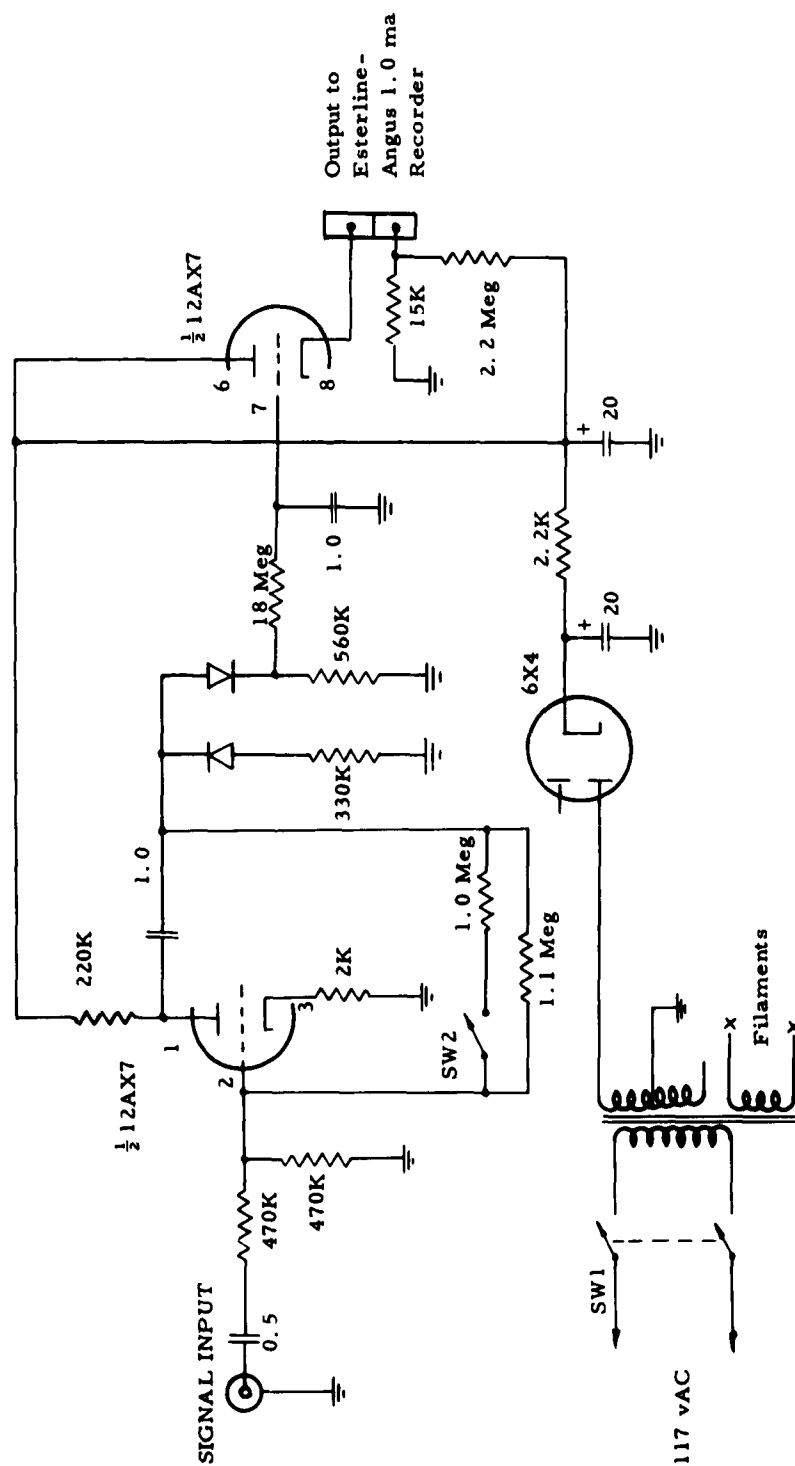
7. Oscilloscope

At all stations, a Heathkit Model 0-12 Oscilloscope was provided for the purpose of trouble shooting and waveform observation. Its response and sweep characteristics are not entirely satisfactory for observation of the lower frequencies of interest, but it represented a practical compromise between cost and performance.

H. Noise Problems

There are many possible sources of noise in measurements of this type, and all of them have been encountered at one time or another during the program. The principal sources are vibration of the sensors in the earth's steady magnetic field, electromagnetic fields of man-made origin at the sensors, and instrument noise in the measurement equipment itself.

The natural fluctuations to be measured are of the order of 0.1 to 10 milligammas. If the sensor is initially at right angles to the earth's steady field of about 50,000 gammas, a change in this angle of only 0.01 seconds of arc will change the field along the sensor axis by more than two milligammas. Very small vibrations of the sensor will therefore induce spurious signals, and the frequency range of interest here is one in which mechanical vibrations are rather easily induced. They may be induced by action of the wind on



Notes:

1. All capacitance values in microfarads
2. SW2 is "calibrate-operate" switch.
(shown in "operate" position)

Figure 15. Integrated-Activity Recorder Drive Unit

the detector shelter, or if there are trees nearby, the vibrations may be transmitted to the tree roots and thence through the ground. At Thule, where high winds were frequent, no trees existed, and the detector shelter was covered by a mound of dirt and snow, but wind noise was still transmitted through the ground. For this reason, wind records have been kept wherever possible. Man-made vibrations can also be troublesome if vehicles or machinery are operated nearby; airplanes flying overhead also produce this type of noise.

Electromagnetic noise is usually associated with electric power distribution lines. The 60 cps noise (always present since the equipment is operated on ac power) is filtered out in the amplifier, and in most locations the higher order harmonics (180 cps usually being the strongest) for which the filtering is less effective, are not large enough to cause trouble. On some power systems, one or more of the higher harmonics can be troublesome. If the power lines in the vicinity carry heavy currents, transients on the lines will produce noise in the 1 to 50 cps range which cannot be filtered out, and this noise will be largest for the vertical component. At Fort Devens, for example, this noise was appreciable on the vertical component but negligible for the two horizontal components. Rotating electrical machinery operating at less than 3000 rpm (50 rps) can also produce appreciable noise, often at 30 cps (1800 rpm). In one case, the 30 cps noise due to a refrigerator at the Mt. Evans site could be eliminated. At Thule, diesel-generator power systems were very troublesome. At Shickley, the 30 cps noise is large on the vertical component but negligible on the horizontal components.

The principal sources of instrument noise have been thermoelectric noise and flicker noise in the first amplifier tubes: both sources of noise have been most troublesome at the low frequencies near 1.0 cps. Since the signal voltages induced in the sensor at these frequencies are small fractions of a microvolt and are still only a few microvolts at the first amplifier grid on the secondary side of the input transformer, this noise must be reduced to a minimum. The thermoelectric noise is reduced by thermally shielding the soldered connections in the input circuitry; this reduces the rates of change of temperature at the connections so that the residual thermoelectric voltages do not vary at frequencies of 1.0 cps or higher. The flicker noise in the amplifier tubes has been reduced by the use of precisely regulated dc (or batteries) for the amplifier tube heaters; this also eliminates power line transients in the heater currents which greatly aggravated the flicker effect in the early stages of the project. It is still necessary to check and replace the first amplifier tubes periodically to keep this noise to a minimum.

A final source of noise has been the tape flutter in the magnetic tape transport which reduces the dynamic range of the recordings as previously noted. If the amplifier gains are set somewhat low, this tape flutter becomes an appreciable source of noise when the tapes are played back.

I. Reliability

Reliability has continually been a problem. Failure or malfunction of any one of many components could put the station out of operation, or make the recorded data questionable, and often did. Probably the most common source of trouble in this respect was the tape deck and its controls, and the most common type of malfunction in this unit would be the failure of the idler roller to pull in sufficiently to permit the drive spindle to start the tape. Poor voltage regulation and intermittent failures of the ac power source were great problems at Thule and Alaska. Low ac voltage was a common cause of malfunctioning of the tape transport as previously noted.

Other common troubles were timer breakdown, relay failures, tube aging, etc. An early cause of timer trouble was the use of dc timing motors which did not stand up in field operation. The use of ac motors improved reliability but introduced timing errors at stations with poor frequency regulation of the ac power. At Thule a system accurate to one second per day or better was developed in 1959 using a 60 cps tuning fork oscillator; a crystal clock was also used from time to time; it was more accurate but also more prone to breakdown.

In some units the plate resistor of the 6AS6 in the FMO tended to overheat and fail. This was readily corrected and has not been a source of trouble since.

But by far the most common trouble was operator error, particularly in calibration scheduling and timing, gain changing and setting, and failure to set the equipment for proper operation after tape changing and calibration.

J. Accuracy of Recorded Data

1. Basic Accuracy of Calibration

The method of calibration, described previously, utilizes a 1% precision resistor in the measuring circuit, and the individual

resistors in series with each calibration coil are also within 1% of nominal value. The calibration meters have rated accuracy of 3%. Thus the total calibration current is known to about 4%, and the current in each calibration coil will be within approximately 1% of its nominal value of one-third of the total calibration current. Therefore the calibration current in each coil is accurate to 5%, probably better. The circuit used is shown in Figure 16.

The absolute calibration of any individual sensor, assuming no error in the basic calibration against the cube coil, probably does not differ by more than 5% from the "true" value. Since the basic calibration procedure is a comparison measurement, its accuracy is probably somewhat better than the accuracy of the meters used. Estimating this error as 2%, it may be seen that the calculated data from the individual recording channels is probably not in error by more than 7%, if the reduction process may be assumed error-free. Overall accuracy is certainly better than 10%. Relative error between the individual channels of a single station however will be much less. Differences here will probably not exceed 2% from the mean calibration. These levels of error do not appreciably affect the value of the data obtained, however, since most of its information content lies in the variation of signal level with time rather than its absolute value at any given time.

2. Gain Changes and Other Time Effects Between Calibrations

With this equipment, as with any equipment which requires adjustment and maintenance, it was inevitable that adjustments and changes would be made at times when it was inconvenient or impossible to make complete notes or to perform recalibrations. Thus, in addition to normally expected slow changes in gain characteristics and center frequency of the FMO, some abrupt changes in the level of recorded data have been encountered which make interpretation very difficult. In normal operation it was considered desirable to have two periods of calibration signal on each tape, one at the start and the other at the end. These calibration periods should follow a regular frequency pattern, so that each of the six frequencies would appear once in each group of three tapes in an orderly sequence. No gain changes should be made between calibrations. Many exceptions to this pattern exist in the data as received, however. Initially, when the systems were set up, a full set of calibrations would be run before recording started.

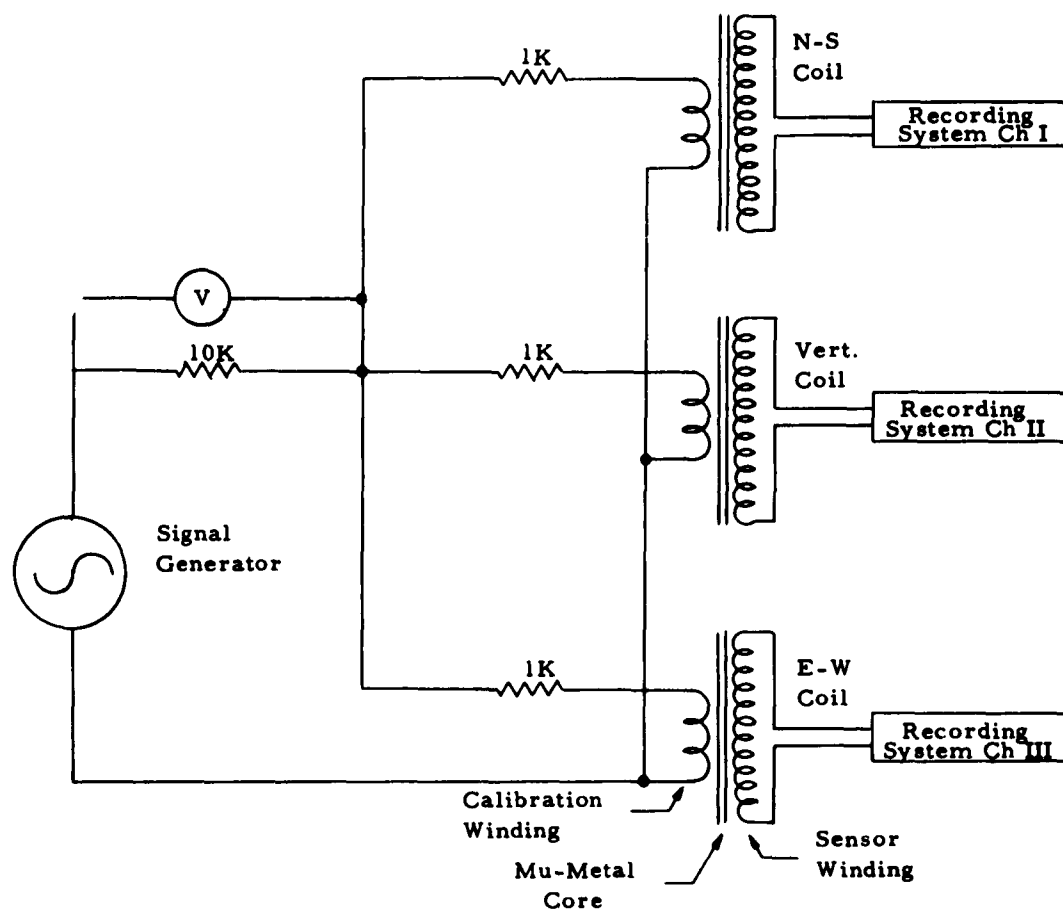


Figure 16. Calibration Circuitry

Time of calibration is also an important factor. It is desirable that the period of calibration be exactly 15 minutes with the present system so that it will be comparable with other calibrations without correction. Experience has indicated that it is difficult to achieve this condition unfailingly in field operation, and there are many instances of calibrations too short and too long. This can be corrected for in the reduction process, if necessary.

3. Means for Increasing Accuracy of Future Data

In any future recording system of this kind, it would be highly desirable to incorporate in design and construction the maximum possible degree of discrimination against operator error and other sources of uncertainty in the data. A major defect in the past has been the lack of sufficient training and adequate written instructions for the field station operators. Even with improved equipment, a competent operator will still be the prime requisite.

The following are suggested as possible approaches for improving the quality of recorded data:

- a. Greater emphasis is needed on means for aiding the operator to evaluate recording system performance in the field. A monitoring device such as the integrated-activity recorder is a minimum requirement, and an oscillograph for observing and recording waveforms is highly desirable.
- b. Gain controls should be adjustable only in discrete reproducible steps, not continuously.
- c. Greater use should be made of feedback and other means of stabilizing gain and center frequency against change of component values, line voltage variations, and temperature changes to minimize time variation of recording system performance.
- d. All calibration periods should be automatically timed, or calibration timing circuits should be incorporated in the reduction system. Probably both are desirable.
- e. A special calibration waveform (noise, for example) might be used to provide simultaneous calibration of all frequencies of interest in one calibration period. While

it is problematical whether this would actually improve the quality of data over the single-frequency method previously used, it would result in a saving of time and an increased certainty and confidence in the data.

K. Recording System Response

1. Response of the Sensor-Amplifier System

Tests of the frequency response of the recording system up to the modulator input were made for most of the stations. This response includes the effect of the sensor characteristic, the input transformer, and the amplifier proper. Figures 17 through 20 show this overall frequency characteristic for the recording equipment used at Denver, Alaska, Thule, and Fort Devens. The method used to obtain it was to establish a constant current in the calibration coil at each of a number of frequencies, and to read the resulting output at the monitor point of the amplifiers immediately preceding the input to the modulator stage.

2. Response of the Modulator-Demodulator System

To test the overall linearity of the modulation-demodulation process using the tape as the intermediate link, signals were recorded at 10 cps at the Denver station on tape #148, using a constant input level. Tape speed for recording was the standard 0.3 ips. The standard playback speed of 30 ips was used. Figure 21, obtained in this way, demonstrates the linearity of the conversion between the signal at the input to the modulator during recording and the signal at the output of the demodulator during playback. The y-axis intercept represents the zero-signal noise level due to flutter in both the recording and playback systems, and is of the order of 0.01 volt. Linearity is good, and it may be concluded that this portion of the overall system offers little in the way of problems in obtaining valid data with the possible exception of instability of the modulator center frequency, which is carefully checked at each tape change to minimize this.

Frequency response of the modulator-demodulator system was also tested. For this purpose, the level of the calibration signal was set to give 0.2 volts rms at the monitor jack, and 15 minute recordings were made at the frequencies 2, 5, 7, 10, 20, 30 and 50 cps. Additional runs were made at levels of 0.4 and 0.6 volts rms. Before each

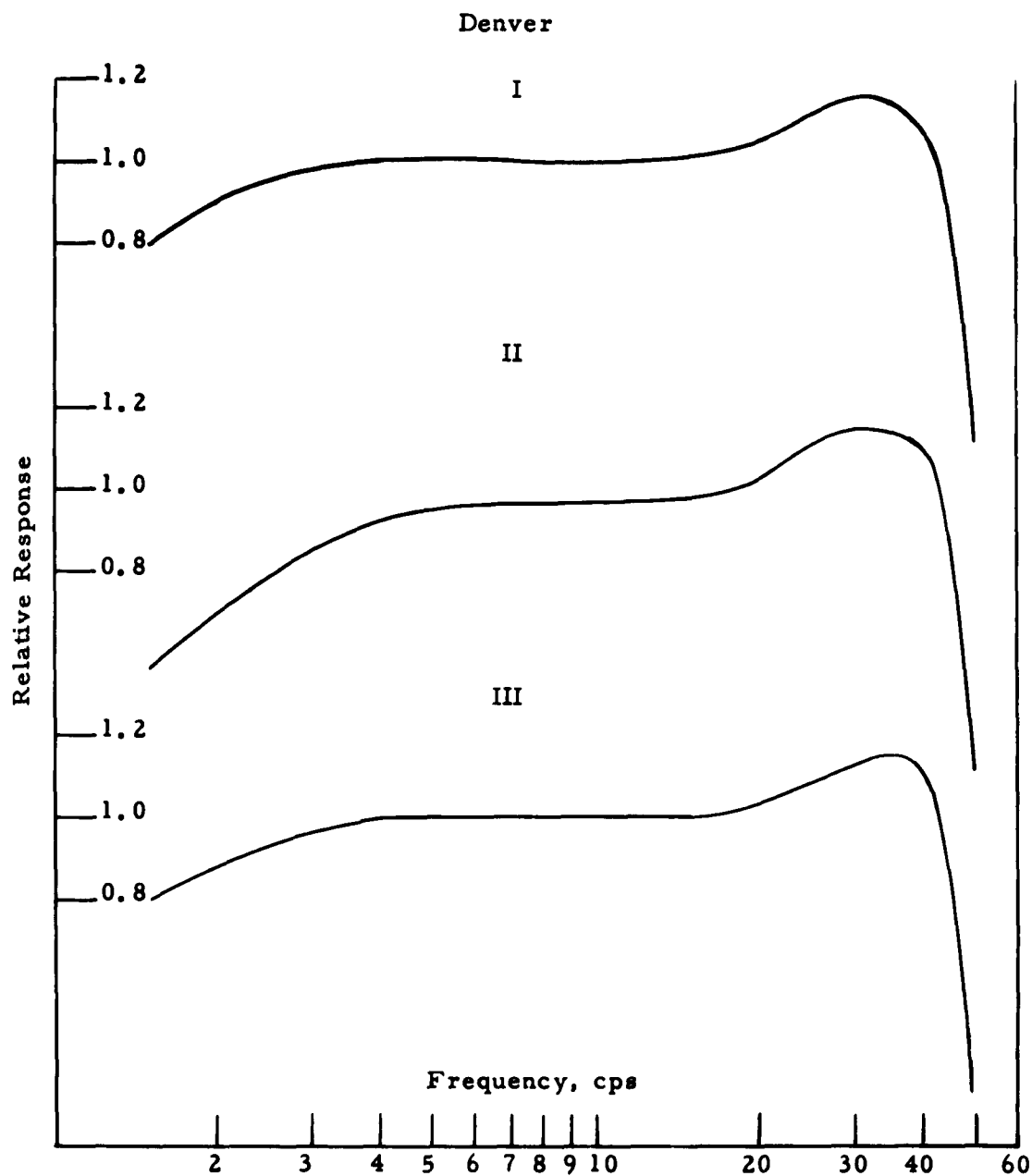


Figure 17. Sensor-Amplifier System Response - Denver

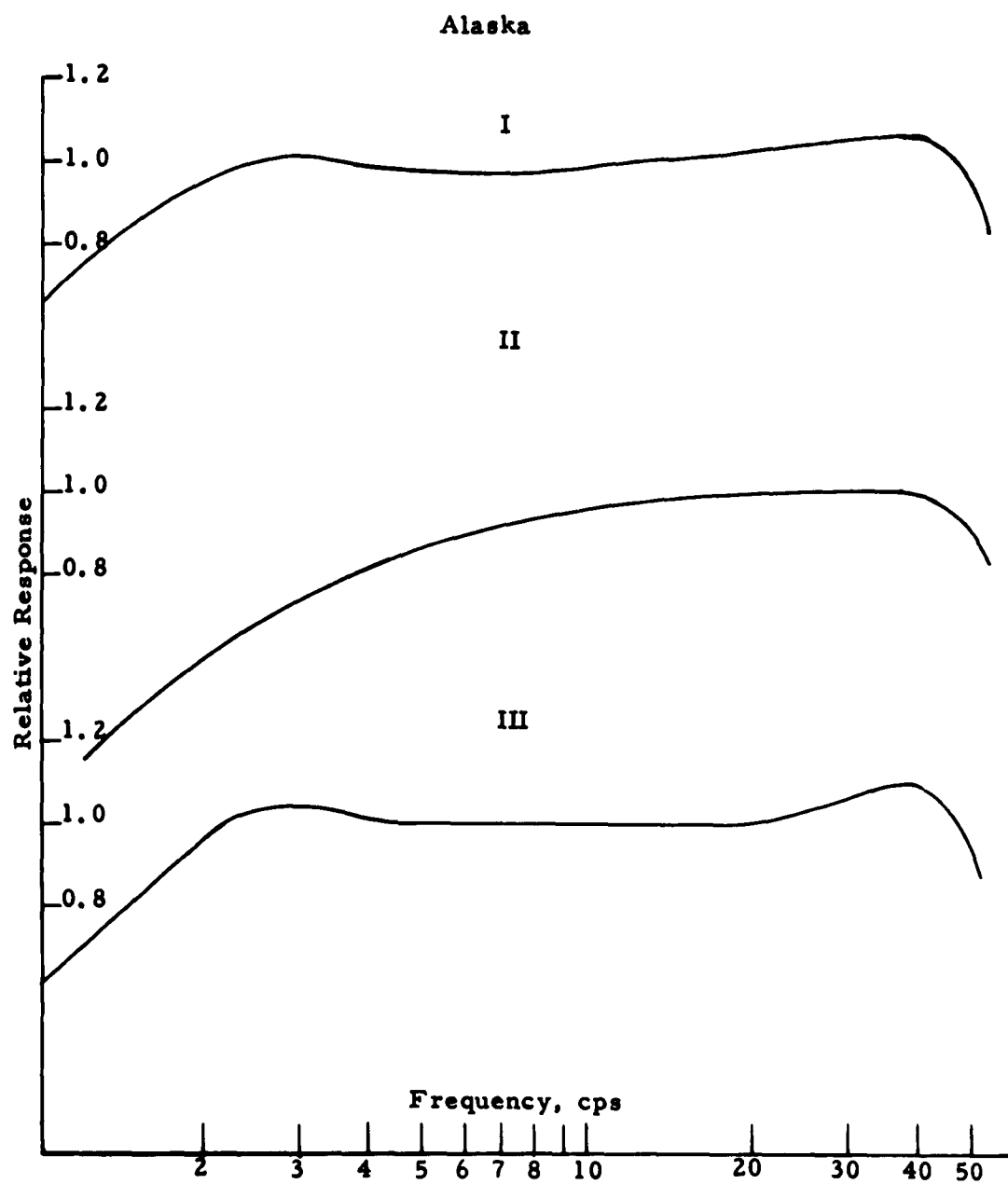


Figure 18. Sensor-Amplifier System Response - Alaska

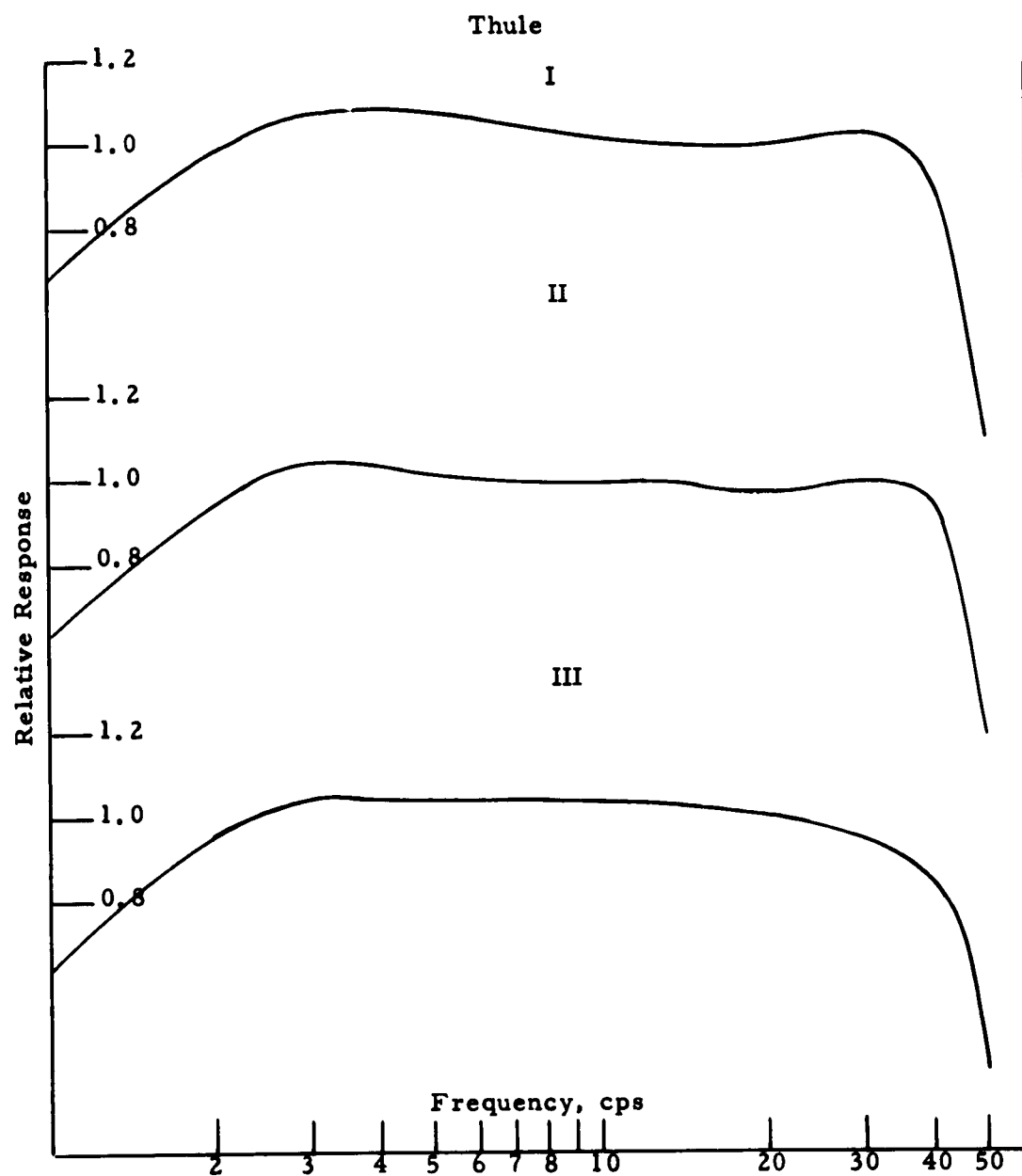


Figure 19. Sensor-Amplifier System Response - Thule

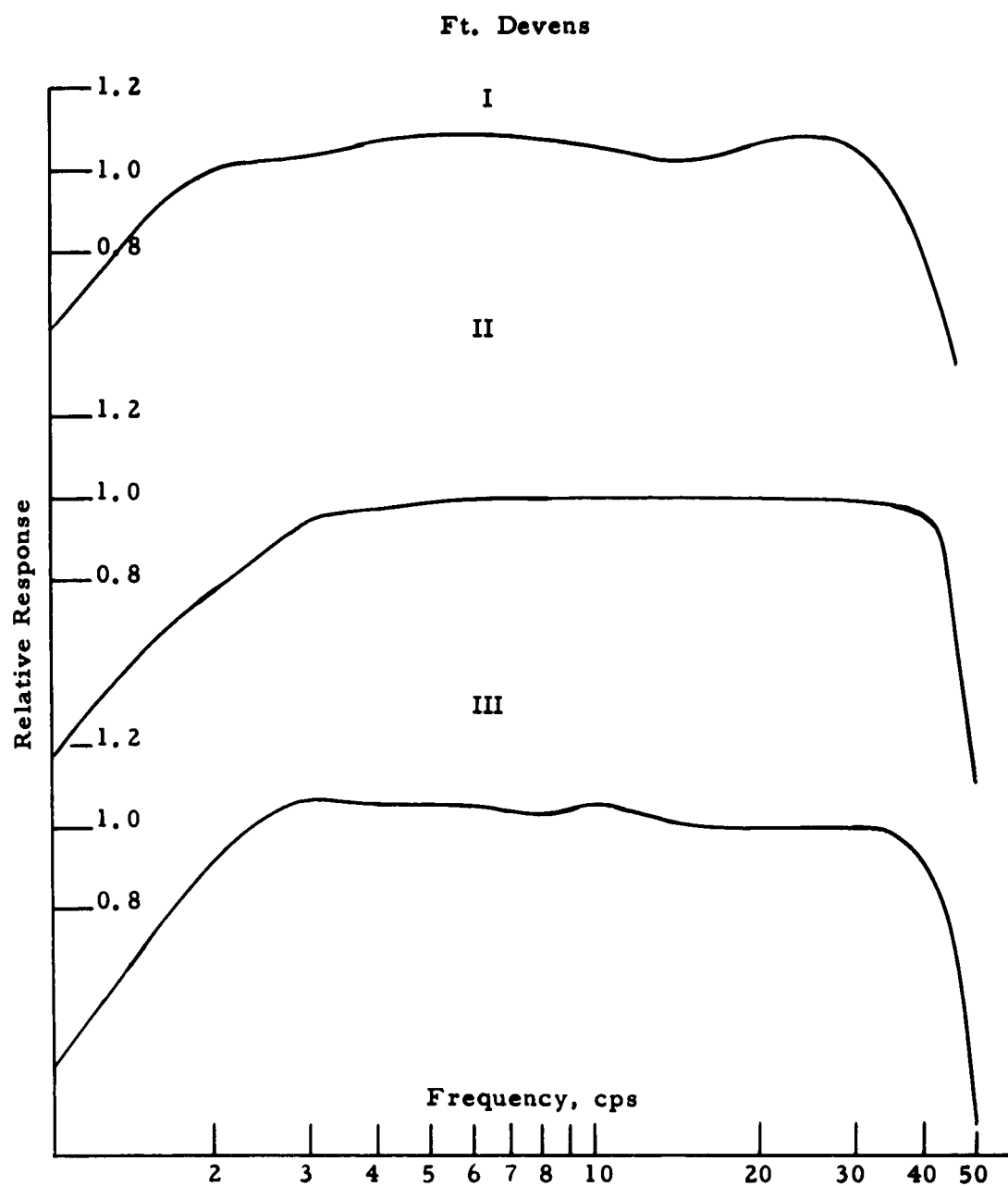


Figure 20. Sensor-Amplifier System Response - Fort Devens

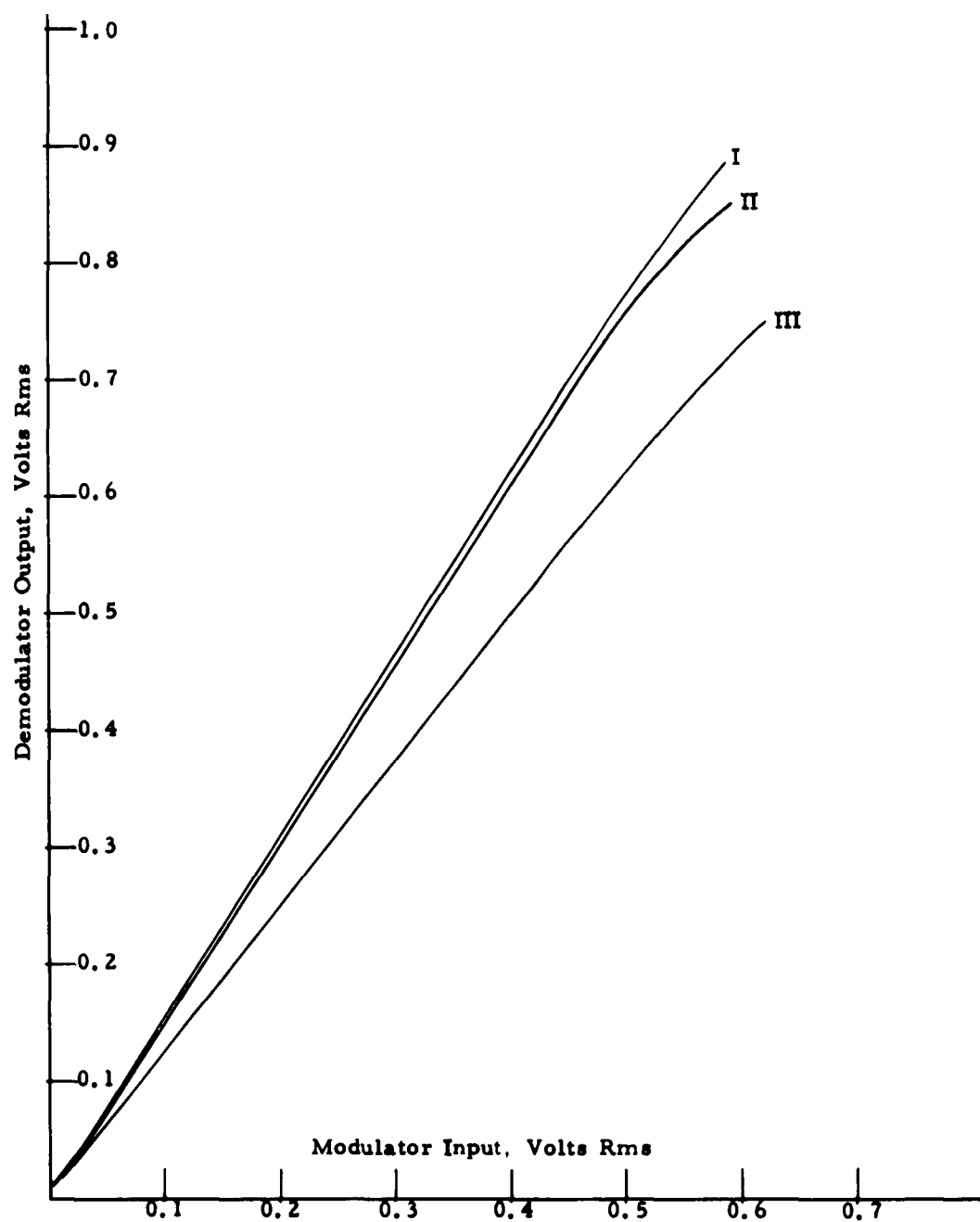


Figure 21. Modulation-Demodulation Characteristic: Denver

period of recording, the modulators were checked for proper adjustment and center frequency. The resulting curves are shown in Figure 22, and represent the voltage output of the demodulators when the test tapes at the different frequencies are played back.

3. Recording Amplifier Stability

Tests of the recording amplifiers at the Denver station were made starting 12 July 1960, continuing through August 1960. Data were taken for Channel I only, at frequencies 2.75, 5.0, 10, and 20 cps. The maximum measured deviation from the mean gain over this period was $\pm 6\%$, a substantial part of which may well have been measurement error.

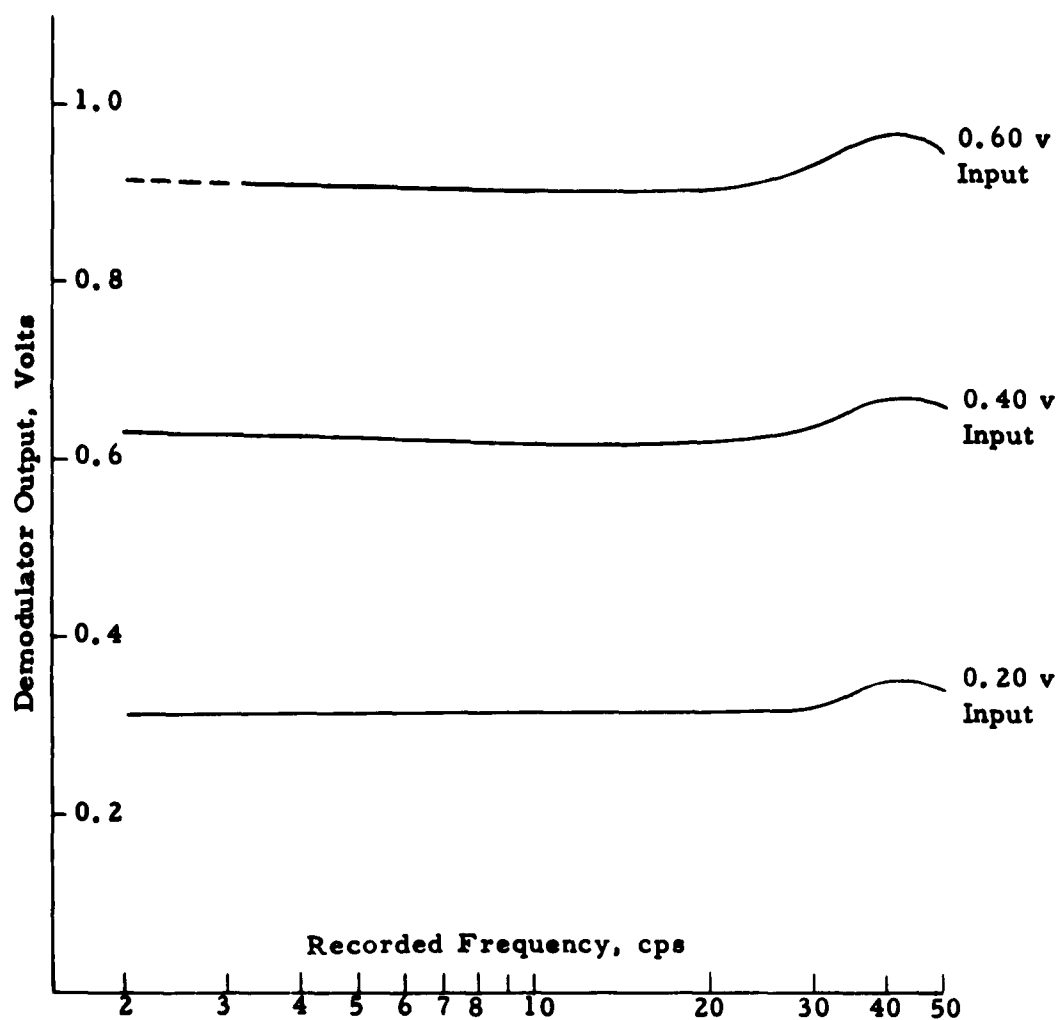


Figure 22. Demodulator Output versus Frequency: Channel I, Denver

III. DATA REDUCTION SYSTEM

The purpose of the data reduction system is to remove geomagnetic fluctuation information from the magnetic tape, average or integrate the level of the signal within octave frequency bands for each recording period, and to provide numerical output suitable for analysis.

The regular recording cycle consists of continuous recording during the first 15 minutes of each hour. The recording equipment is then turned off for 45 minutes before recording is resumed for the next 15 minute period. The interruption of recording results in a short section of blank tape, or "carrier break". This carrier break is utilized for timing synchronization in the playback and reduction process. Continuous recording has been employed for some periods at Denver and has recently been initiated at the Shickley and Huancayo stations, but these recordings are momentarily interrupted every 15 minutes to provide the needed carrier breaks.

In the reduction process, each of the three FM signals from the tape playback heads is demodulated, amplified, and filtered into six bands covering approximately one octave each to provide a broad base for analysis. See Figure 23, "Block Diagram: Data Reduction System". Each filtered signal is then rectified and accumulated in a simple RC integrator of 50 second time constant, equivalent to a 5000 second time constant at the original recording speed. The voltage level appearing on the integrator capacitor after a standard integrating time of 9 seconds (equivalent to 15 minutes of original recording time) is considered to be proportional to the integral or average of the magnetic activity recorded for that period.

This capacitor voltage level is converted to numeric form using a standard analog-to-digital method. The electronic digital computer is considered the most feasible tool available at present for reduction and analysis of this quantity of data, and the computer installation at DRI dictated the form of the output data. The data input to the computer at the time the reduction equipment was first assembled was via punched paper tape, but card input is now used. See Figures 24 (a), 24 (b), "Data Flow, Reduction System & Computer".

A. Tape Transport

The playback tape transport used for the reduction equipment is an Ampex S-3230 operating at a tape speed of 30 inches per second.

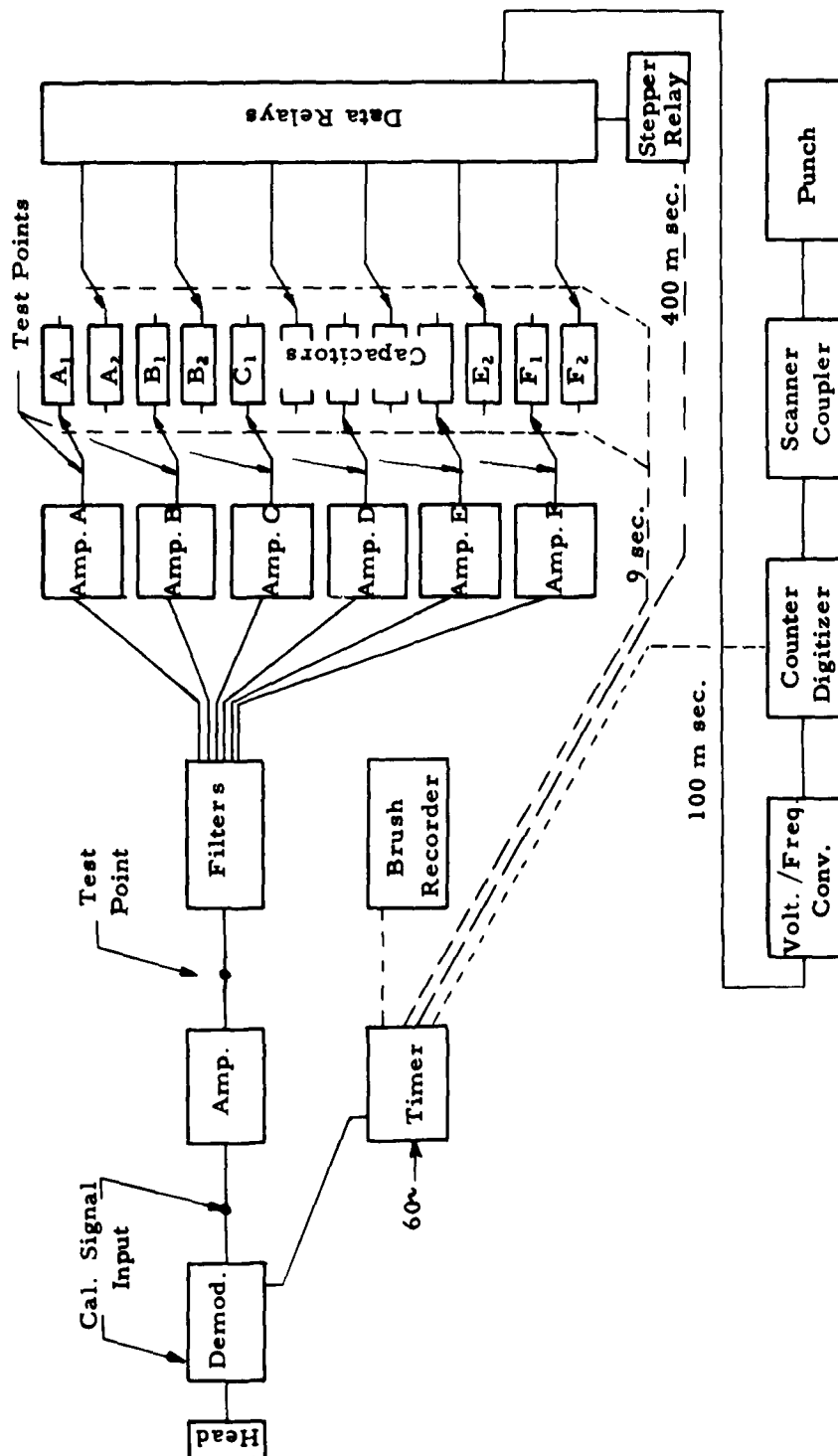


Figure 23. Block Diagram: Data Reduction System

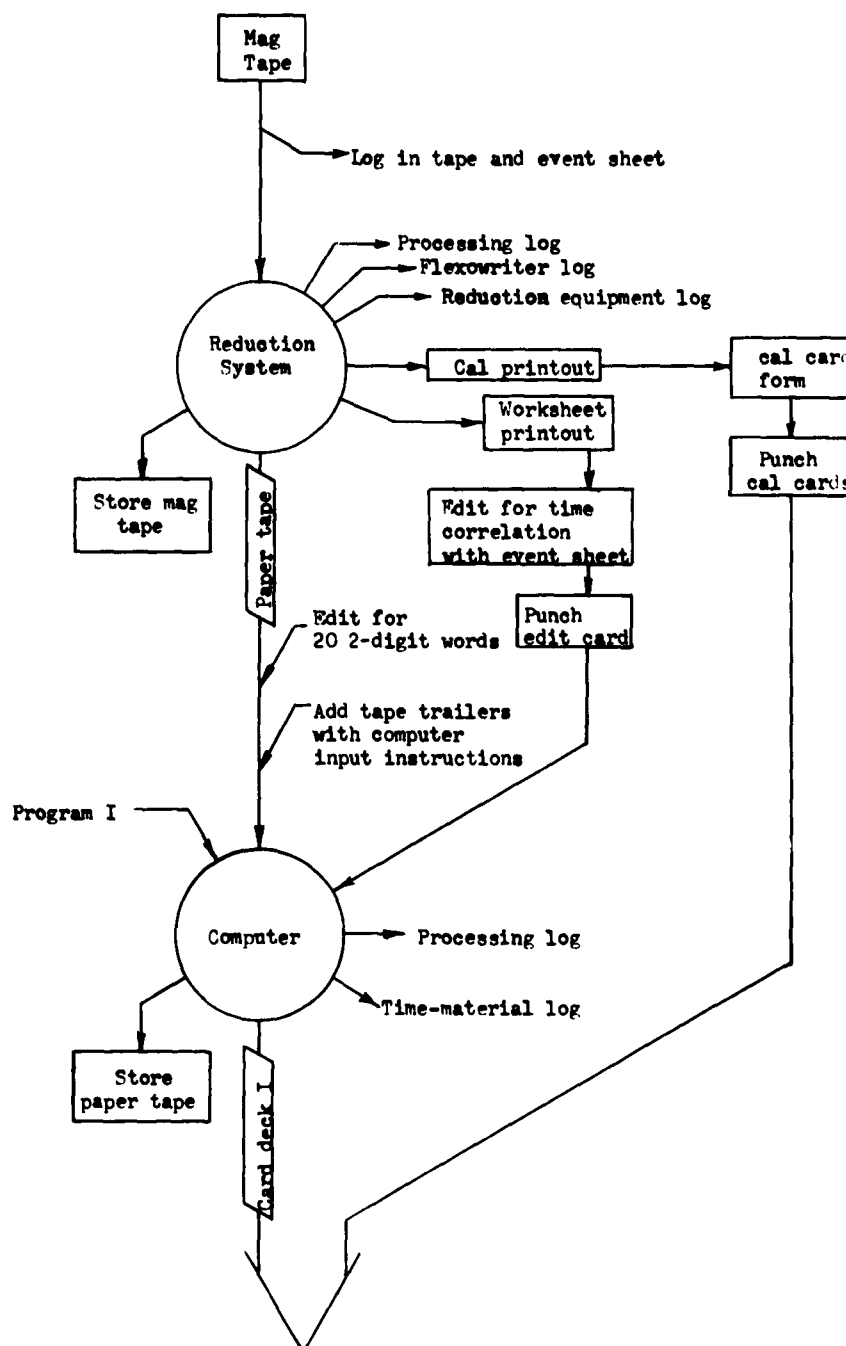


Figure 24-A. Block Diagram: Data Flow, Reduction System and Computer

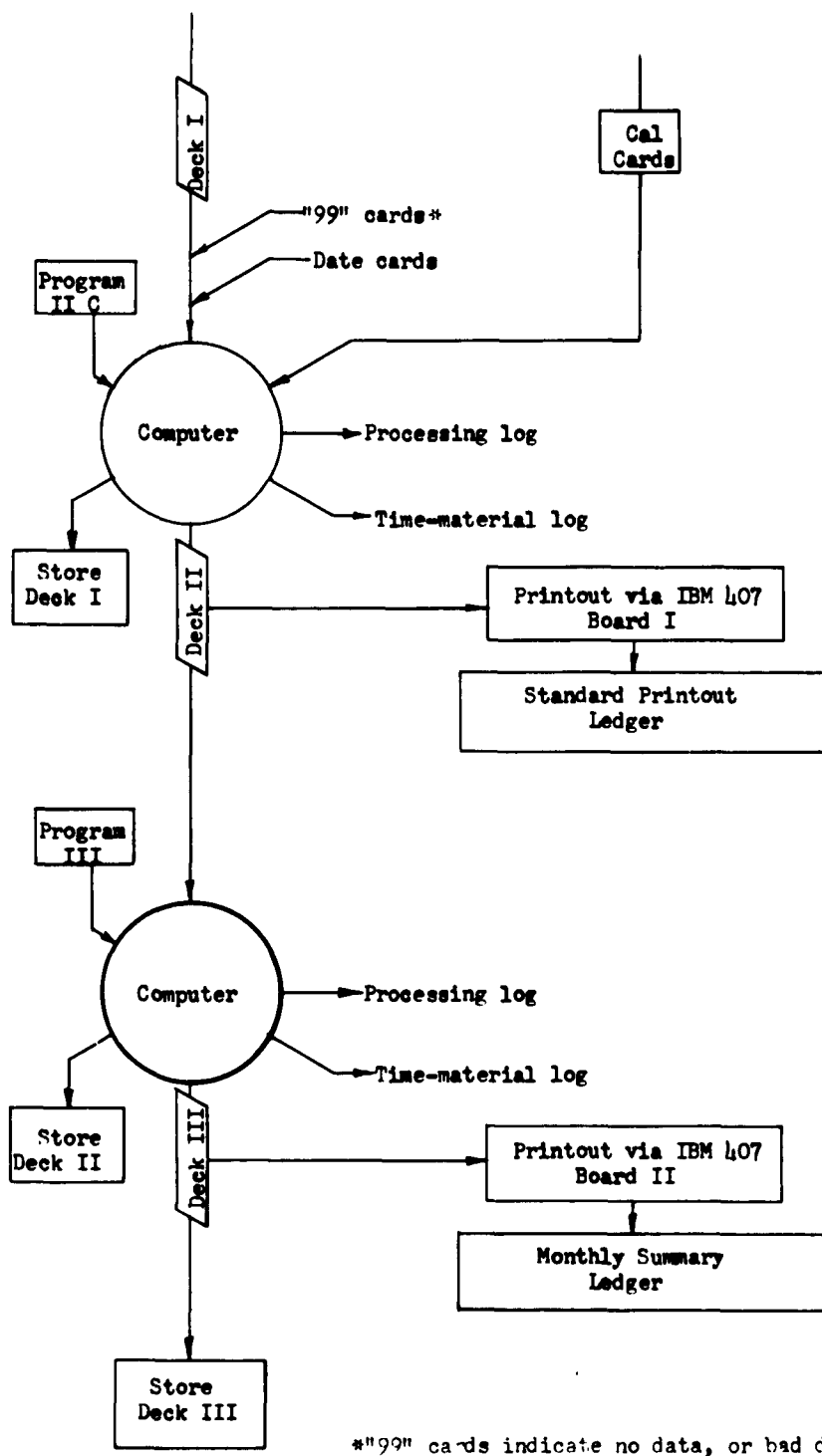


Figure 24-B. Block Diagram: Data Flow, Reduction System and Computer

This speed is 100 times greater than the recording speed of 0.3 inches per second and thus the 15-minute recording is played back in 9 seconds. The playback heads are set up for a three-track system on 1/4-inch tape with the following spacing:

Each track is .050 inches wide

Channel II is centered on the tape

Center-to-center distance between tracks is .070 inch

B. Demodulators

The demodulators are modified Ampex FR1100 units. The three channels are identical electrically. The demodulator circuit, shown in Figure 25, consists of three stages of amplification and clipping, a phase inverter, discriminator, cathode follower, low pass filter, and output cathode follower. The first three stages amplify the frequency-modulated carrier from the playback heads, clipping it to form a square wave. This square wave is differentiated to form exponential pulses of standard area. A phase inverter then feeds these pulses to the twin diode discriminator, whose output is fed through a low-pass filter to the output cathode follower. The output voltage is thus proportional to the frequency of the signal on the tape.

C. Channel Amplifiers

The output of each demodulator is coupled to its amplifier through a 30 kilohm multi-turn precision potentiometer. In these so-called channel amplifiers, as shown in Figure 26, two stages of amplification with cathode follower output provide a maximum gain of 33.

D. Filters and Post-Filter Amplifiers

The output of the channel amplifier is fed in parallel to six one-octave data filters (and a time-code filter). Each of the three channels is separated in this way into six bands, to give a total of 18 parallel data units. The bands are centered at 150, 275, 500, 1000, 2000 and 4000 cps for data and 5500 cps for the time code. Characteristics of the filters are presented in Figure 27 and tabulated below.

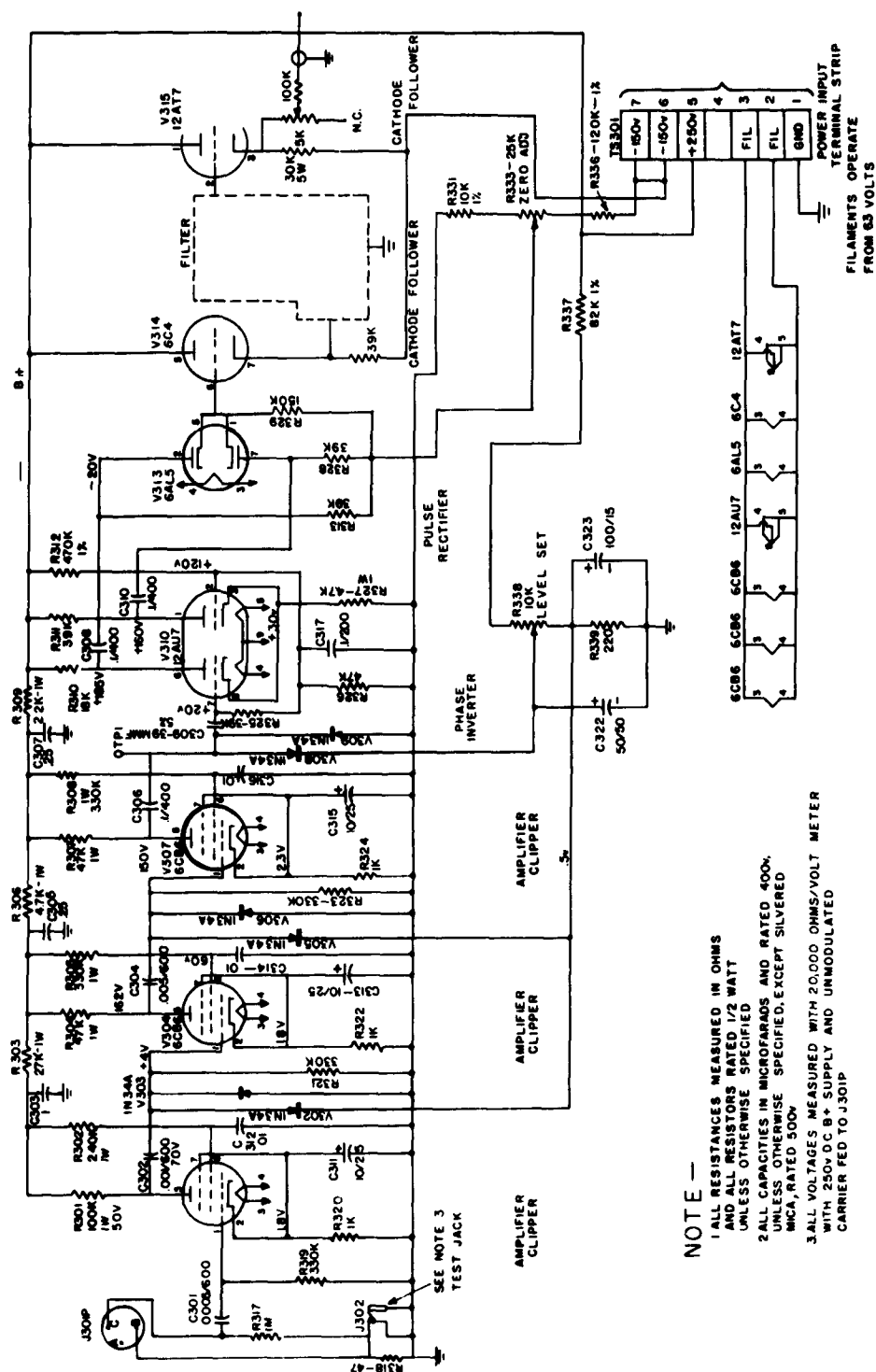


Figure 25. Demodulator

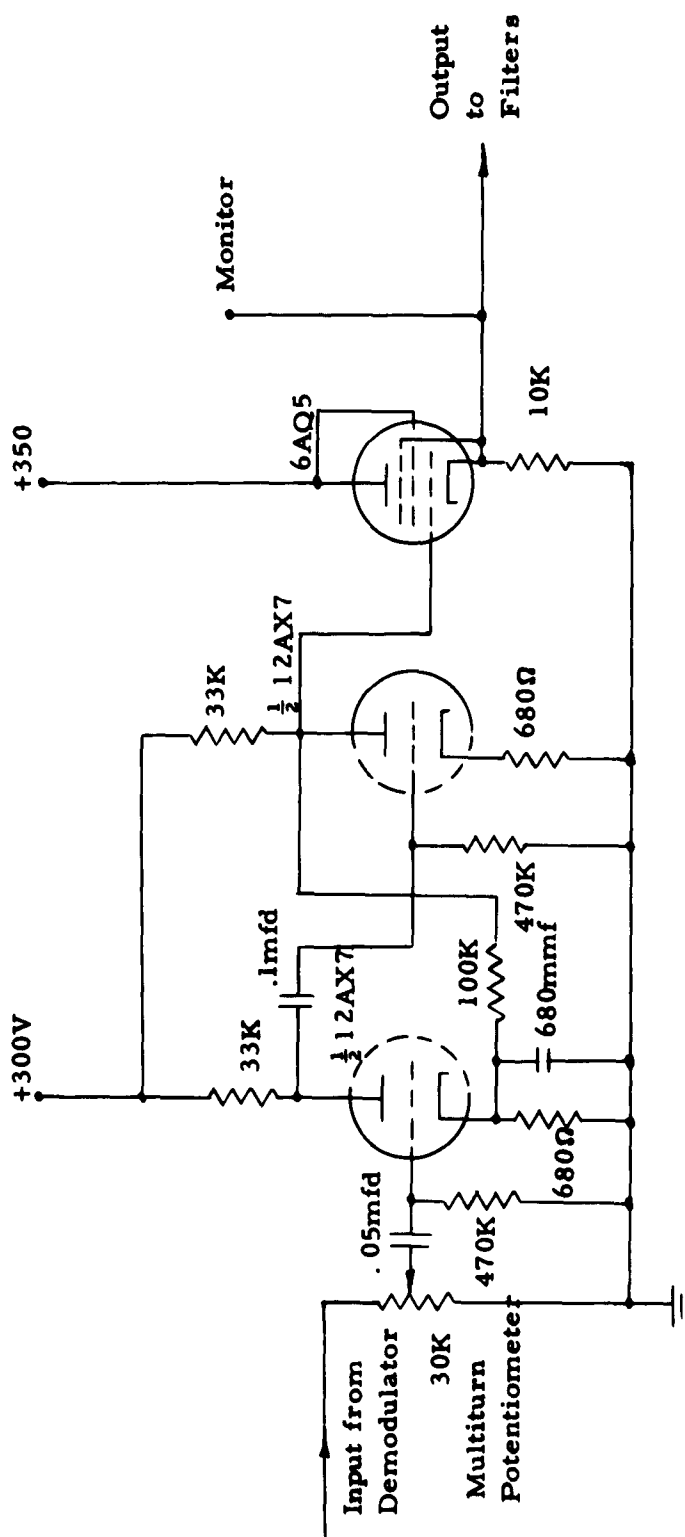


Figure 26. Channel Amplifier

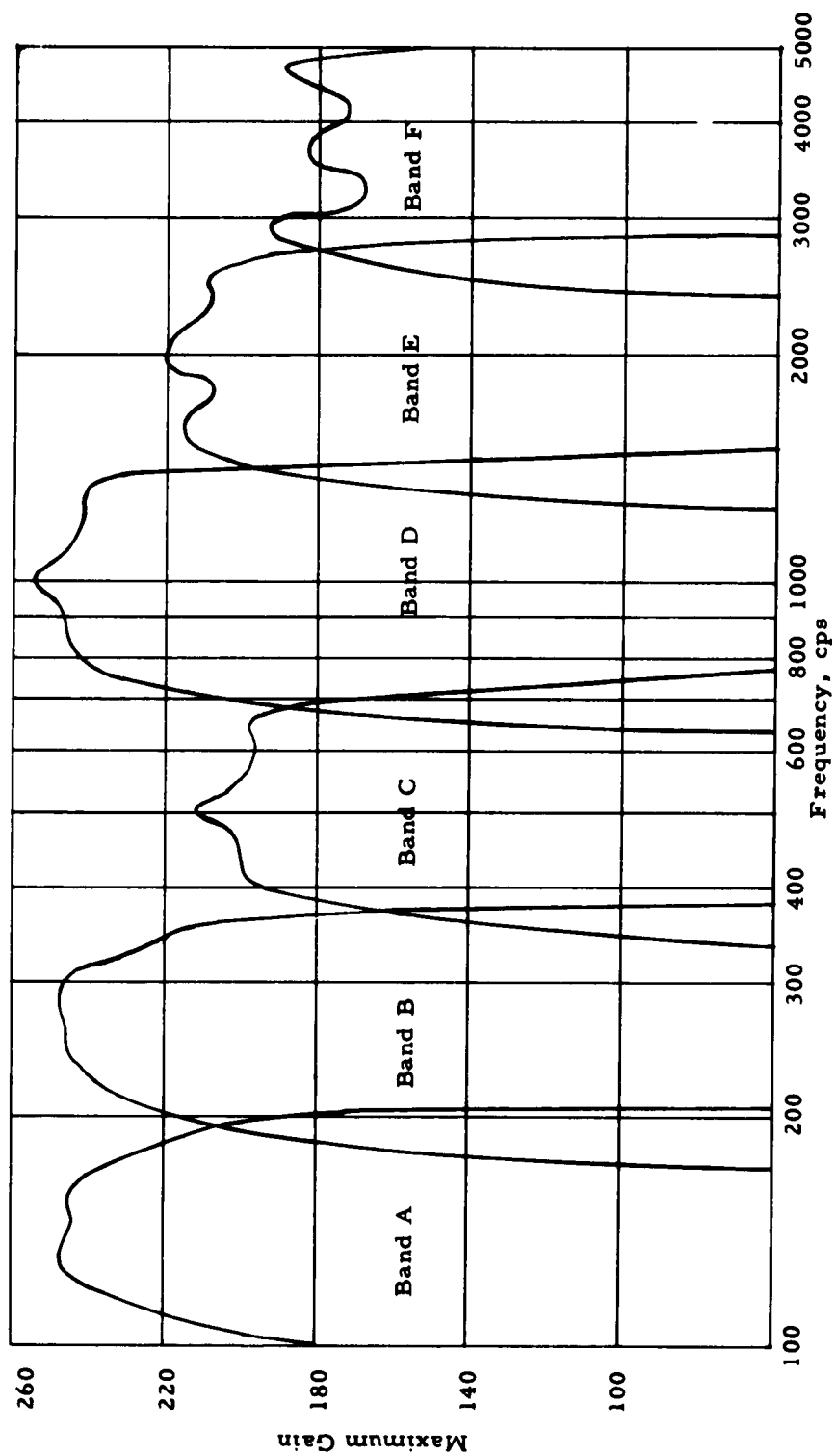


Figure 27. Octave-Band Filter Characteristics

Nominal Center Frequency f_0 , cps	<u>3 db Limits</u>		<u>40 db Limits*</u>	
	Lower f_1 , cps	Upper f_2 , cps	Lower f_3 , cps	Upper f_4 , cps
150	100	192	80	230
275	192	369	153	442
500	369	708	295	850
1000	708	1360	566	1632
2000	1360	2610	1088	3132
4000	2610	5000	2088	5400
5500	5400	5600	5000	6000

* Specifications call for response to be down at least 40 db (from center-band response) from D. C. to f_3 , and from f_4 to infinity.

These frequencies correspond to original frequencies which are 1/100 of the values given because of the 100 to 1 relationship of playback to recording tape speeds. Filter gain is in the range 0.3 to 0.4. The outputs of the 18 filters are individually coupled to 18 "post-filter" amplifiers across a 10 kilohm potentiometer as shown in Figure 28. The maximum gain of the stage is approximately 30.

E. Rectifier-Integrators

The output of the post-filter amplifiers, as shown in Figure 28 also, is rectified and used as the input to an RC integrator consisting of a 50 megohm resistor and a 1.0 microfarad capacitor. The standard charging interval is 9 seconds, corresponding to the period between carrier breaks at the playback tape speed. There are two sets of 18 RC integrators for the 18 data channels. During the first 9 second interval, the first set of integrators is charged. During the following 9 second interval, the first set of integrators is sampled while the second set is being charged, and the cycle continues in this way.

F. Analog-to-Digital Conversion

The voltage level on each capacitor is coupled in turn to the voltage-to-frequency converter. The resulting frequency is counted for 0.1 second by an electronic counter, the digital readout of which is used as a measure of the capacitor voltage. The voltage-to-frequency

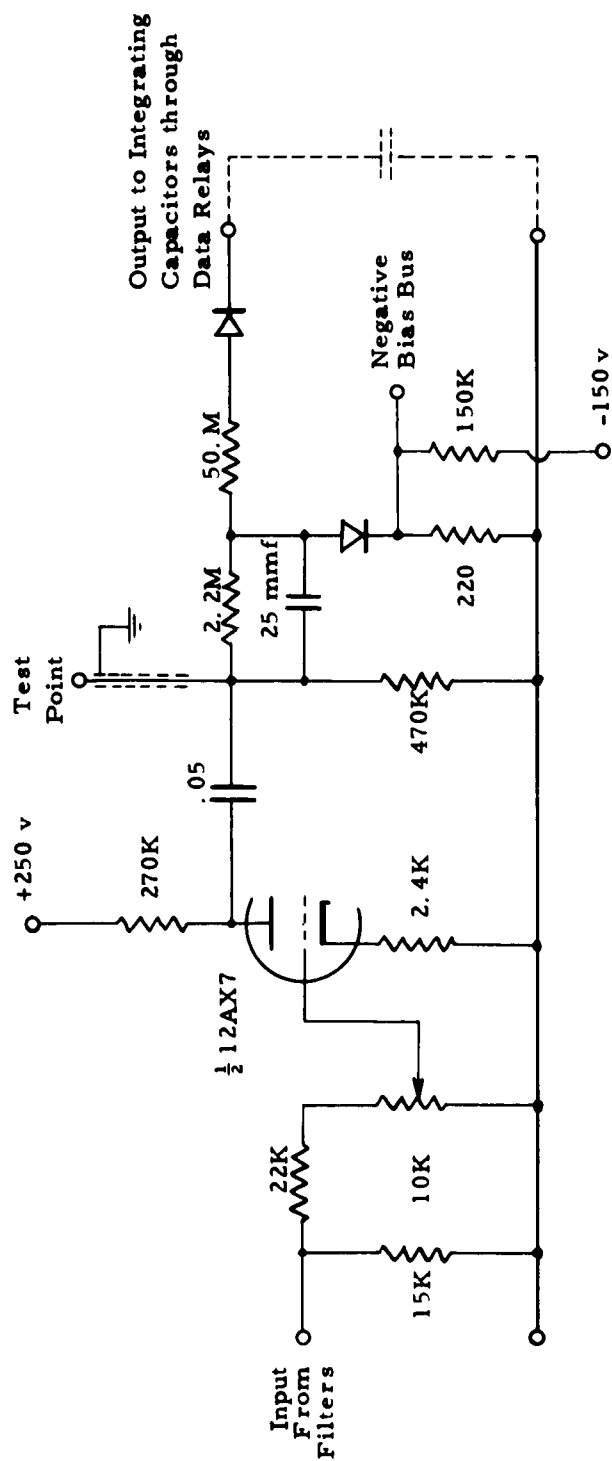


Figure 28. Post-Filter Amplifier Integrator

converter used is a Dymec Model 2210, the counter a Hewlett-Packard Model 521A. The gating period of 0.1 second per capacitor is generated within the timing system. The resulting count is displayed in digital form and also appears at an output connector in teletype code.

A modified Dymec Scanner-Coupler Model 2540 translates the teletype code output to Datatron Code for driving a paper tape punch unit.

G. Timing System

The timer in the data reduction system consists of frequency dividers, gates and drivers. Its function is to supply pulses of the proper magnitude at the proper time in order to program the data flow through the reduction equipment. See Figure 29, "Block Diagram: Data Reduction Timing", and Figure 30, "Data Commutation Timing". A choice of three modes of operation is available. A single cycle of reduction system operation may be initiated in the "manual" mode, with a push button. In the "Free Run" mode a pulse generated by the frequency dividers at the rate of once every 9 seconds will initiate successive cycles continuously. For data reduction, the equipment is operated in the "Automatic" mode, in which the carrier break on the tape serves to recycle the program. See Figures 31 (a), "Reduction System Timer" and Figure 31 (b), "Frequency Divider Circuitry".

A frequency of 60 cps from the A.C. power line is divided successively to yield pulses with repetition rates of 10, 2.5, and 0.111 pps. The 2.5 pps signal drives the stepper switch, which in turn operates the sampling relays. See Figure 32, "Readout Relay Actuation". The 10 pps signal gates the electronic counter. The display time of the counter is set to synchronize the scanner-coupler punching operation with the sampling operation. See Figure 33, "Readout Equipment Control Switching".

The timer also controls the input-output coupling of the integrating capacitors. A transistor latching-relay system is employed as a bistable element to control relays which, on alternate cycles, connect one bank of integrators to the amplifiers for charging. At the same time, the stepper circuitry connects the other bank of integrators sequentially to the sampling and digitizing functions, as shown in Figures 29 and 32. The relays used for input switching are six-pole double-throw telephone type relays.

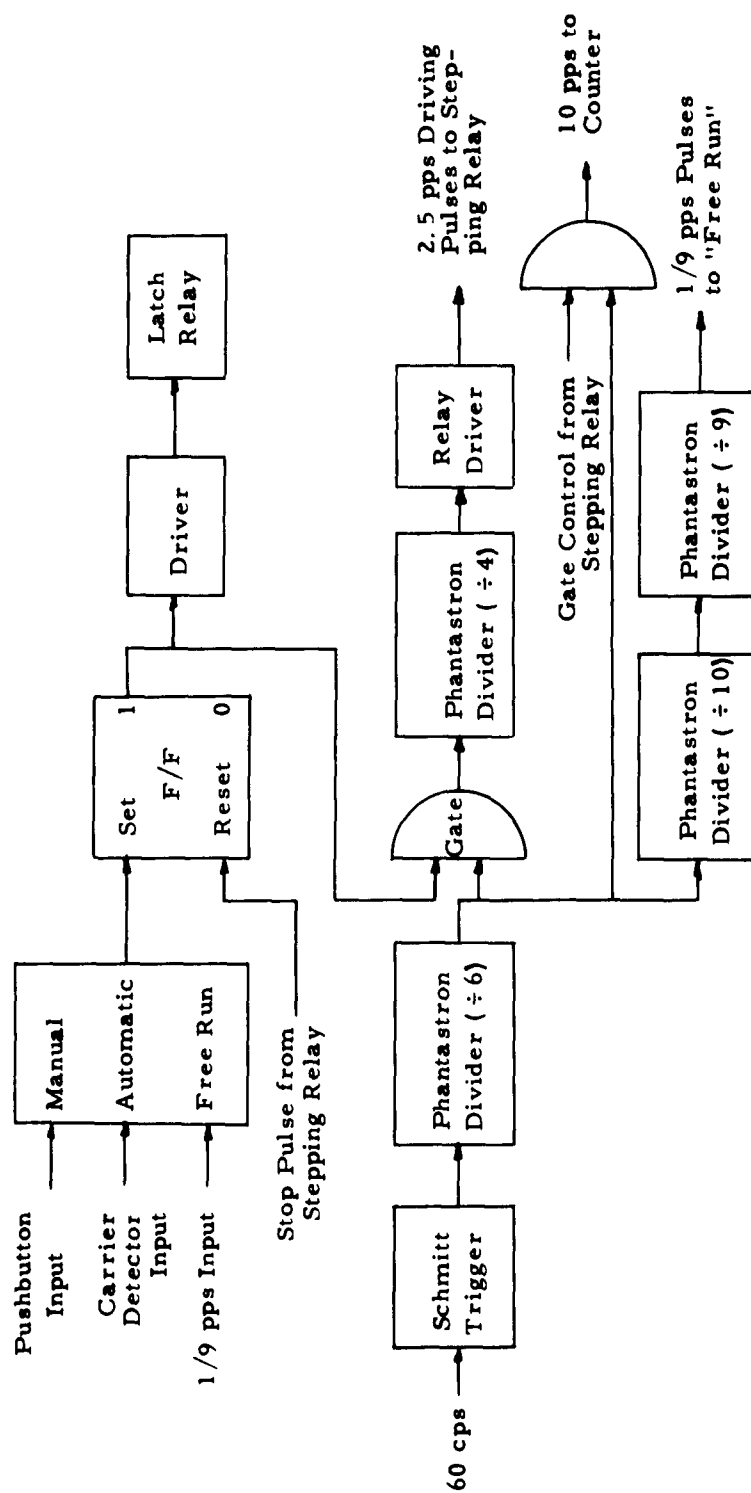


Figure 29. Block Diagram: Data Reduction Timing System

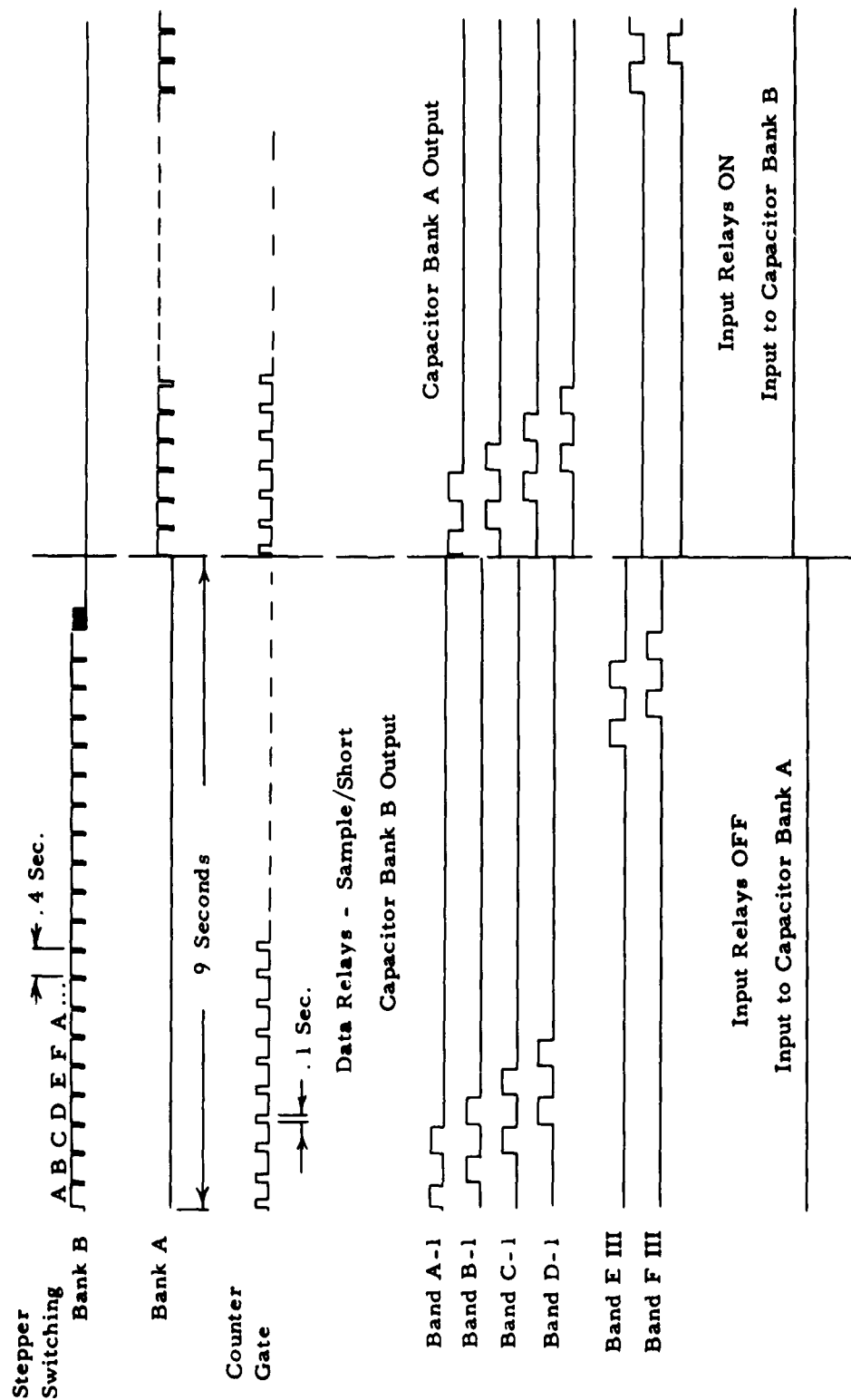


Figure 30. Data Commutation Timing

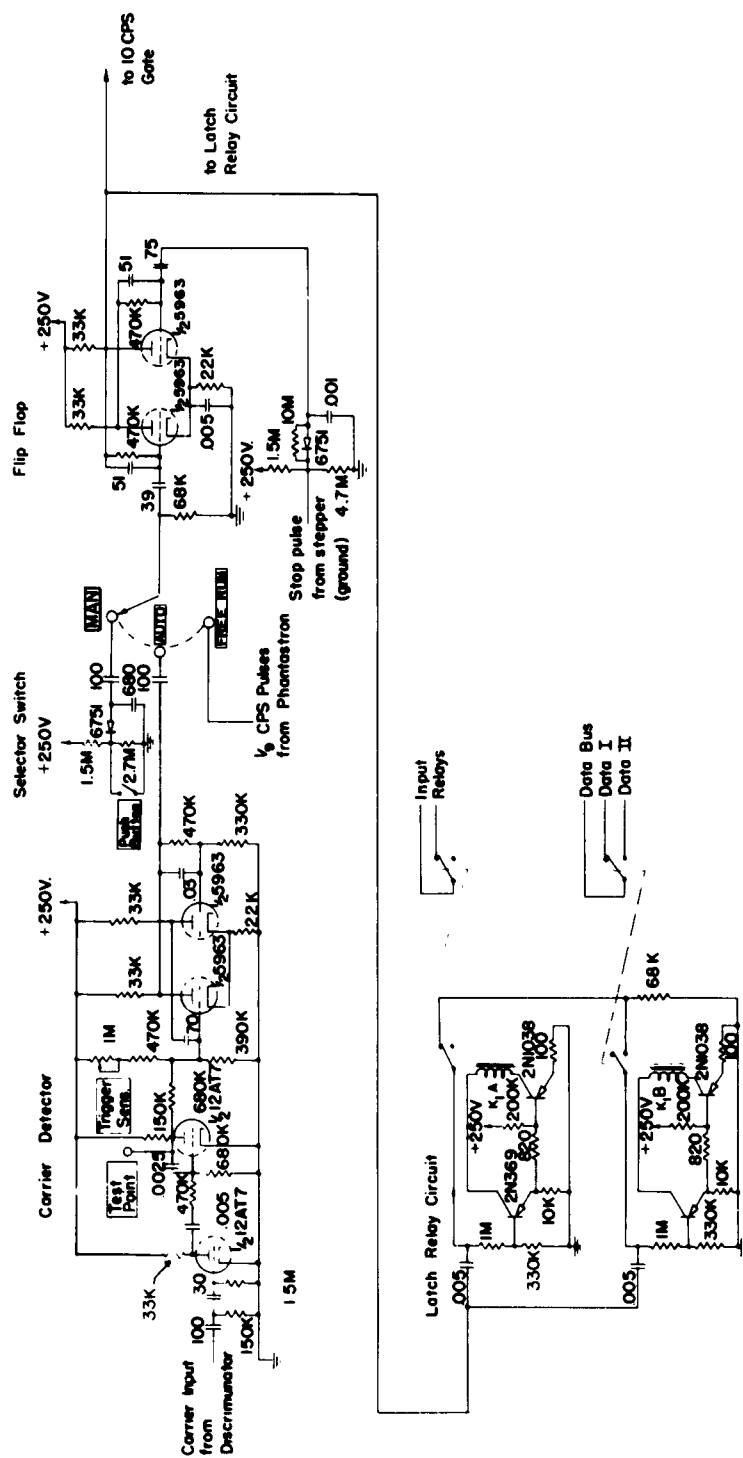


Figure 31-a. Reduction System Timer

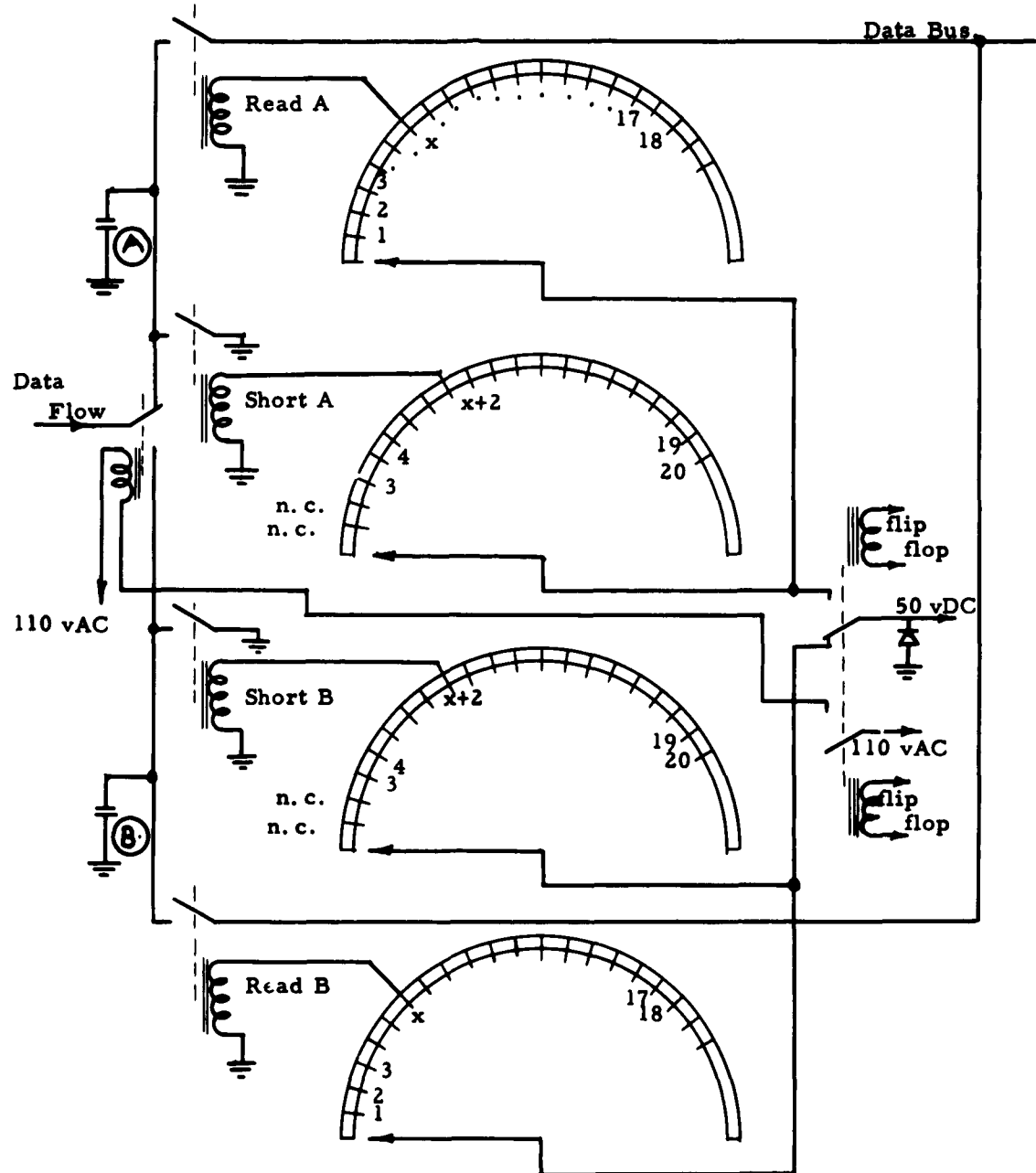


Figure 32. Readout Relay Actuation

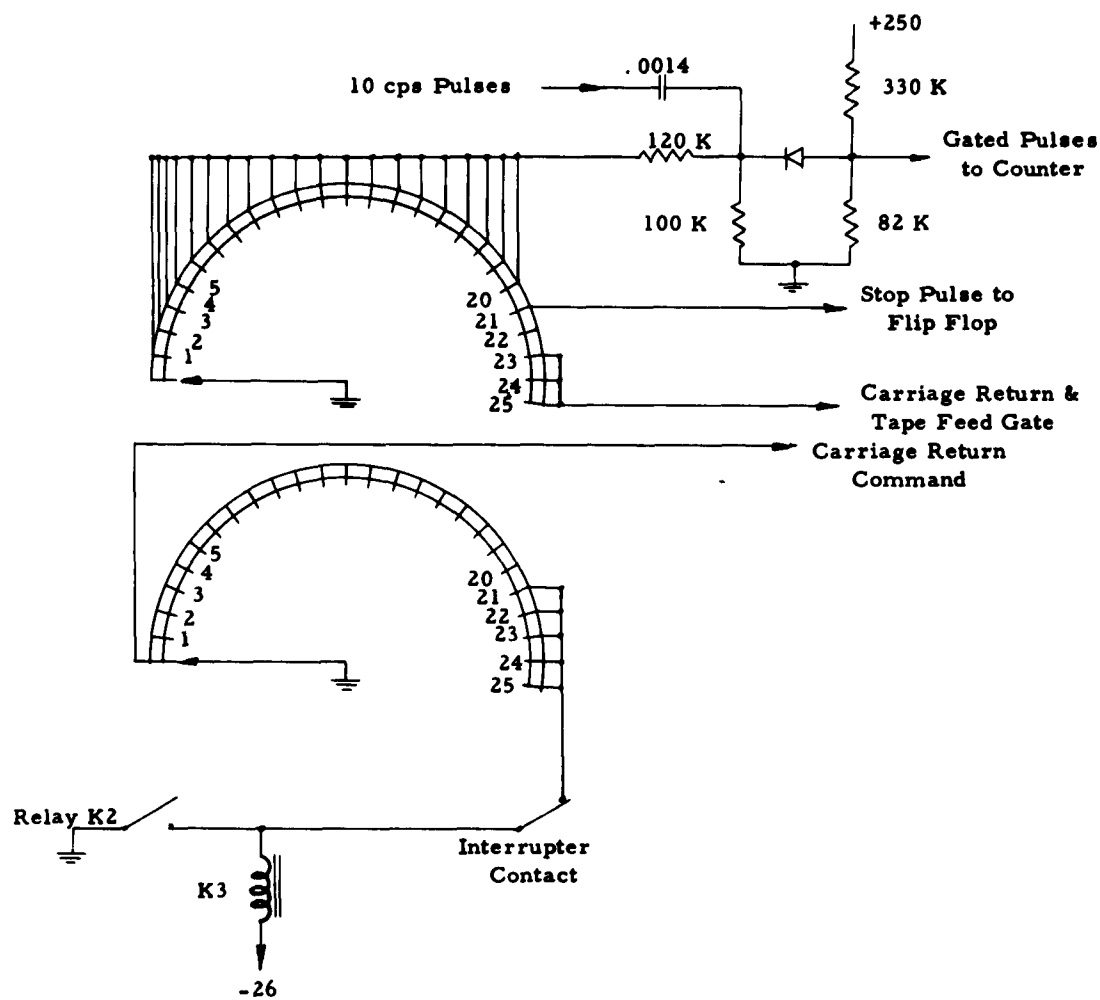


Figure 33. Readout Equipment Control Switching

By this means, the rectified output of each post-filter amplifier is alternately fed to one or the other of the associated integrator capacitors through a common 50-megohm resistor. The duration of the integrating period is controlled by the length of the recording interval and is equal to the time between carrier breaks at playback tape speed. While capacitors in the first bank are being charged, those in the second bank are being read out sequentially. Thus each of the 18 post-filter amplifiers requires two matched integrating capacitors, so that a total of 36 are used.

Readout and shorting of the capacitors is performed by mercury-wetted relays (Clare Type HG1002) controlled by the stepping relay. Beginning with the capacitor representing the data of Channel I, Band A for the previous recording interval, each capacitor is switched in turn to the data bus of the digitizing equipment. The sequence used is the most direct; Channel I, ABCDEF, Channel II, ABCDEF, Channel III, ABCDEF.

When the carrier detector senses the carrier break on the tape, a flip-flop controlled gate passes 2.5 pps pulses to a relay driver circuit, driving the stepping relay at this rate. The stepping relay energizes each mercury-wetted sampling relay in turn, thus accomplishing a serial readout of all 18 capacitors. After each capacitor is sampled, it is shorted to ground through a separate mercury-wetted relay. The shorting operation occurs two steps after the "read" step in order to prevent shorting data to ground by overlap in timing of the sampling and shorting relays. In this system each capacitor requires two mercury-wetted relays, or a total of 72.

Early attempts to perform the sampling function using solid contacts were beset with dry circuit contamination problems, timing troubles, and mechanical failure. The first sampling commutator consisted of a pair of cam-shafts which operated leaf switches, and were driven through clutches by small hysteresis-synchronous motors. The second generation of switching techniques employed a stepping relay as the sampling device. The stepper coil was driven as at present but with the armature leaf connected to the data bus and each contact of the stator connected to one of the 18 capacitors in the read bank. Two alternately connected decks on the stepper performed the sampling function and other decks of the same unit were used for control circuitry. Contact contamination, in combination with the very low levels of potential resulted in a low degree of reliability, and gold plating the contacts was resorted to. Even with this

refinement, the resistance of the contacts soon became variable and resulted in unreliable data. The problem of sampling contact resistance and contamination has been eliminated by the use of hermetically sealed relays with mercury-wetted contacts. These relays are driven by the stepper switch, which permits it to be used at sufficiently high voltage that contact contamination is no problem. Future refinements of the reduction equipment are envisioned, particularly the inclusion of mercury-wetted contacts for switching between the alternate integrator inputs, and rebuilding of the timing unit using commercial digital circuit modules.

H. Playback Level Adjustments

The basic printout from the reduction equipment consists of a line of 18 values of 2 digits each. The values represent the output from each one of six bands in the three channels. Each line represents the activity level in the various bands for one 15 minute recording period. Standard practice is one recording period per hour. Continuous recordings, however, result in 4 recording periods per hour.

In order to establish meaning for this numerical output of the reduction equipment, a signal of known frequency and amplitude is included on the data recording as discussed under calibration (Section II, E.). Initially the playback equipment was adjusted to print out in units of 1×10^{-4} gamma, based on the calibration signal for that particular tape. This proved to be a time-consuming operation because of the necessity for frequent readjustment to compensate for gain changes (intentional and otherwise) between tapes and for different station frequency response characteristics.

An improvement has been in effect, for the most recently reduced 215 recording-days of data, which consumes less time and provides more reliable data. The gain settings of the post-filter amplifiers are adjusted to correspond with the frequency-response characteristics of the particular recording station, so that the output of all channels is as nearly as possible the same. Then the data is scanned and the gains of the channel amplifiers are adjusted so that the maximum feasible output values are obtained without exceeding the range of the two-digit printout system. Since the activity level in each frequency band for each 15 minute recording interval is printed out as a two-digit number, the highest level for each band must be represented by a number less than 99. It is also desirable that the highest level for each band be represented by a fairly large

number, since one unit increment (from 27 to 28 for example) is the smallest increment which can be observed between one recording interval and the next. It should therefore represent a reasonably small percentage change in the activity level. The procedure of adjusting the gains so that the largest numbers obtained are less than 99, but greater than, say 60, thus permits the data system to operate at its greatest precision. Since the two-digit limitation is set by the printout method rather than the data system itself, which can generate three digits, it is possible to obtain three-digit precision in the calibration factors by the following method: the calibration signals on the tape are read through the system to print out the first two digits, and then a rerun is made in the same way to obtain the second two digits, which are then combined to form the three-digit calibration factor. Controls in the system permit either the first two or last two digits to be printed out, but not all three at the same time. These calibration factors are used in the computer to convert the basic printout data into units of magnetic field strength. Units of $\gamma \times 10^{-4}$ have been found convenient, and have been used for much of the data. Other units may be used, however.

IV. COMPUTER PROGRAMS

In the course of this project there have been a number of computer programs either used or prepared for tentative use, and it seems appropriate here to elucidate in some detail their history and the various concepts of data handling and output to provide for missing data, deletion of questionable data, inserting calibration factors, etc.

Two major methods of handling the data from the magnetic tape have been used on this project. The first, as shown in Figure 34, was in use from about June, 1957 to late Fall of 1960. The output of the reduction system was a punched paper tape (ppt) with spaced digital pairs representing uncorrected and unidentified data. Due to the fact that many of the magnetic tapes may have one or more channels missing or questionable, or have lapses in the recording, and all are without identification on the tape proper, it was necessary to edit by hand all paper tapes coming from the reduction equipment.

The only way to identify the data as to time, channel and band was to locate its position in a sequence. This meant that all "holes" in the sequence must be plugged with some identifying symbol which would fill the space and would, in computer language, identify the data either as no good or non-existent for these periods.

Starting and stopping dates and times for the magnetic tapes were recorded by hand on data sheets. Any error in this regard by the recording station operator automatically voided the usefulness of that tape for data purposes, since the tape could not then be correctly identified.

The edited tapes began at 0000 hours local time and ran serially as follows:

Ch. I	Ch. II	Ch. III	Ch. I	Ch. II	Ch. III
ABCDEF	ABCDEF	ABCDEF	ABCDEF	ABCDEF	ABCDEF
1st hr. recording			2nd hr. recording, etc.		

A computer program was developed to identify, in the computer, the data by year, day and hour and to produce a new data tape with corrected signal values and a time code of year, day and hour. The format of the final printout resulting from this program is shown in Figure 35.

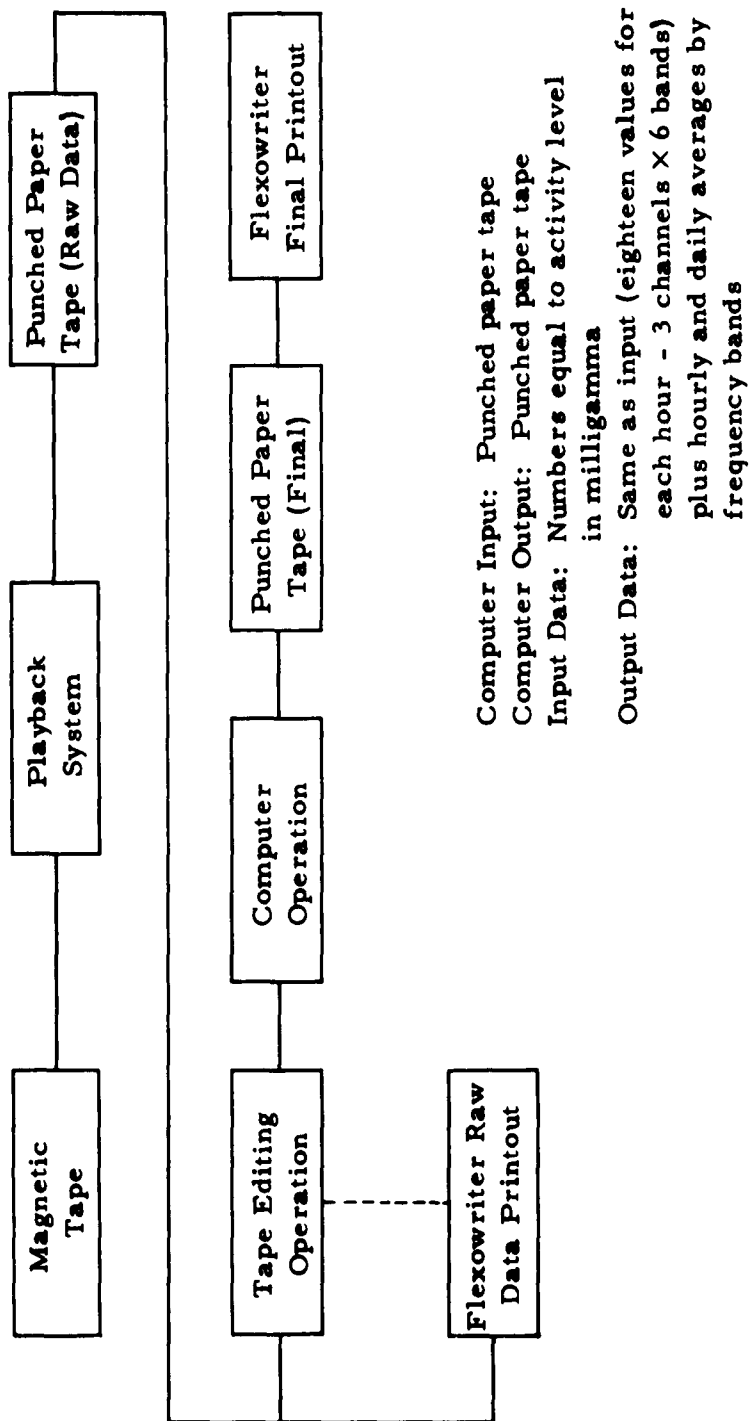


Figure 34. Data Processing System Based on Manual Editing of Punched Paper Tape

DENVER		I												II												III												AVERAGE											
CHANNL-	YR DAY HR	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F												
59	334 00	a ₁	b ₁	c ₁	d ₁	e ₁	f ₁	a ₁	b ₁	c ₁	d ₁	e ₁	f ₁	a ₁	b ₁	c ₁	d ₁	e ₁	f ₁	a ₁	b ₁	c ₁	d ₁	e ₁	f ₁	a ₁	b ₁	c ₁	d ₁	e ₁	f ₁	a ₁	b ₁	c ₁	d ₁	e ₁	f ₁												
59	334 01	a ₂	b ₂	c ₂	d ₂	e ₂	f ₂	a ₂	b ₂	c ₂	d ₂	e ₂	f ₂	a ₂	b ₂	c ₂	d ₂	e ₂	f ₂	a ₂	b ₂	c ₂	d ₂	e ₂	f ₂	a ₂	b ₂	c ₂	d ₂	e ₂	f ₂	a ₂	b ₂	c ₂	d ₂	e ₂	f ₂												
59	334 02	a ₃	b ₃	c ₃	d ₃	e ₃	f ₃	a ₃	b ₃	c ₃	d ₃	e ₃	f ₃	a ₃	b ₃	c ₃	d ₃	e ₃	f ₃	a ₃	b ₃	c ₃	d ₃	e ₃	f ₃	a ₃	b ₃	c ₃	d ₃	e ₃	f ₃	a ₃	b ₃	c ₃	d ₃	e ₃	f ₃												
59	334 03	a ₄	b ₄	c ₄	d ₄	e ₄	f ₄	a ₄	b ₄	c ₄	d ₄	e ₄	f ₄	a ₄	b ₄	c ₄	d ₄	e ₄	f ₄	a ₄	b ₄	c ₄	d ₄	e ₄	f ₄	a ₄	b ₄	c ₄	d ₄	e ₄	f ₄	a ₄	b ₄	c ₄	d ₄	e ₄	f ₄												
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59	334 20	a ₂₁	b ₂₁	c ₂₁	d ₂₁	e ₂₁	f ₂₁	a ₂₁	b ₂₁	c ₂₁	d ₂₁	e ₂₁	f ₂₁	a ₂₁	b ₂₁	c ₂₁	d ₂₁	e ₂₁	f ₂₁	a ₂₁	b ₂₁	c ₂₁	d ₂₁	e ₂₁	f ₂₁	a ₂₁	b ₂₁	c ₂₁	d ₂₁	e ₂₁	f ₂₁	a ₂₁	b ₂₁	c ₂₁	d ₂₁	e ₂₁	f ₂₁	a ₂₁	b ₂₁	c ₂₁	d ₂₁	e ₂₁	f ₂₁	a ₂₁	b ₂₁	c ₂₁	d ₂₁	e ₂₁	f ₂₁
59	334 21	a ₂₂	b ₂₂	c ₂₂	d ₂₂	e ₂₂	f ₂₂	a ₂₂	b ₂₂	c ₂₂	d ₂₂	e ₂₂	f ₂₂	a ₂₂	b ₂₂	c ₂₂	d ₂₂	e ₂₂	f ₂₂	a ₂₂	b ₂₂	c ₂₂	d ₂₂	e ₂₂	f ₂₂	a ₂₂	b ₂₂	c ₂₂	d ₂₂	e ₂₂	f ₂₂	a ₂₂	b ₂₂	c ₂₂	d ₂₂	e ₂₂	f ₂₂	a ₂₂	b ₂₂	c ₂₂	d ₂₂	e ₂₂	f ₂₂	a ₂₂	b ₂₂	c ₂₂	d ₂₂	e ₂₂	f ₂₂
59	334 22	a ₂₃	b ₂₃	c ₂₃	d ₂₃	e ₂₃	f ₂₃	a ₂₃	b ₂₃	c ₂₃	d ₂₃	e ₂₃	f ₂₃	a ₂₃	b ₂₃	c ₂₃	d ₂₃	e ₂₃	f ₂₃	a ₂₃	b ₂₃	c ₂₃	d ₂₃	e ₂₃	f ₂₃	a ₂₃	b ₂₃	c ₂₃	d ₂₃	e ₂₃	f ₂₃	a ₂₃	b ₂₃	c ₂₃	d ₂₃	e ₂₃	f ₂₃	a ₂₃	b ₂₃	c ₂₃	d ₂₃	e ₂₃	f ₂₃	a ₂₃	b ₂₃	c ₂₃	d ₂₃	e ₂₃	f ₂₃
59	334 23	a ₂₄	b ₂₄	c ₂₄	d ₂₄	e ₂₄	f ₂₄	a ₂₄	b ₂₄	c ₂₄	d ₂₄	e ₂₄	f ₂₄	a ₂₄	b ₂₄	c ₂₄	d ₂₄	e ₂₄	f ₂₄	a ₂₄	b ₂₄	c ₂₄	d ₂₄	e ₂₄	f ₂₄	a ₂₄	b ₂₄	c ₂₄	d ₂₄	e ₂₄	f ₂₄	a ₂₄	b ₂₄	c ₂₄	d ₂₄	e ₂₄	f ₂₄	a ₂₄	b ₂₄	c ₂₄	d ₂₄	e ₂₄	f ₂₄	a ₂₄	b ₂₄	c ₂₄	d ₂₄	e ₂₄	f ₂₄
																										DAILY AVERAGE												M _a M _b M _c M _d M _e M _f											

DAILY AVERAGE

M_a M_b M_c M_d M_e M_f

Notes: 1. $A_1 = \frac{a_1 + a_2 + a_3}{3}$, etc. 2. Initial printout format same as shown, except no headings or averages are given. 3. Subscripts indicate hour of day, superscripts indicate channel, letter proper indicates frequency band.

Figure 35. Format of Final Printout Used with Tape-Editing System

This data flow system worked, but it had several disadvantages. One of these was in the handling of the data in the editing phase. The raw data tapes were a record, in serial form on punched paper tape, of the actual contents of the magnetic tape. To edit into 24-hour periods, to remove bad data from the sequence, and replace the "holes" with an appropriate number of previously prepared punched tape symbols involved cutting and splicing punched paper tape. Unavoidably, it was a tedious, time-consuming job. Unless extreme care was taken, further slowing the work, errors could readily occur. It required a very high degree of cooperation between the operator of the reduction equipment and the tape editor, but it appeared necessary with the computer facility available at that time. When additional computer equipment became available, making possible conversion from punched paper tape to punched cards, the advantages to be gained in time and accuracy were deemed sufficient to justify a radical change in the data flow procedures.

In the second method, used since Fall, 1960, the magnetic tapes were reduced in the same manner as before. The changes in procedure involved only the editing and tape-to-card conversion. Two new computer programs were written, tested, and used in this second phase. The first was a comparatively simple one. Its function was to convert the information contained in the punched paper tape to punched cards, one hour's information per card. This program resulted in 18 three-digit computer words of data, a three-digit code word for the station, and the magnetic tape number. After this operation, the actual editing took place.

Working from the data sheets filled in by the recording station operator, the cards for chronological days and hour were broken up into 24-hour groups. In front of each daily pack of 24-hour cards, a hand-punched card with the code word identifying the particular day and station was inserted.

Also, cards corresponding to periods of no recording or bad data, were removed from the card deck, and prepunched cards with the symbol for bad data or no data were inserted. One card was used for each hour to be filled. This was necessary because the program was written so that the computer would accept only 25 cards at a time (24 hour cards, 1 day identification card). The computer automatically stopped if there were too few or too many cards.

After the cards were manually edited, the data on them was fed into the computer to be operated upon. This called for another program, which gave the same results as were obtained in the first

program after the computer operated upon the edited paper tape. This resulted in a deck of punched cards which gave the hourly values and their average for each of six bands plus a summary card which gave daily averages for all six bands of each channel making a deck of 25 cards for each day. From this deck the final data printout was made, and had the same form shown in Figure 35.

The savings of time and effort realized by the use of cards over punched paper tape were substantial. Also, the versatility for further analysis work was greatly enhanced, since the cards may be sorted into any combination desired for later computer operations.

In both of the foregoing methods, the data was operated upon in essentially the same way in the computer. The values used for the computer input were actual milligram levels as determined by the data-reduction apparatus with the calibration data set into its gain controls. Also, the means obtained were those of the three hourly values (one in each channel) for each frequency band, and the 24 hour means were the means of these.

About this time it was suggested by Mr. Maple that a saving of time and increased reliability of data could be realized by establishing a fixed response characteristic in the data-reduction system and using the calibration data in the computer program. This requires timing of the calibration signal to insure that all data are reduced on an equivalent basis. Previously calibration was accomplished by the operator in the reduction system. At the time it was decided that the single-band three-channel averages were actually not needed, and that it would be preferable to have 24 hour averages of each band-channel combination. Accordingly, two new computer programs have been developed. Figure 36 shows the flow of data in the first one, which is designed to give a summation and mean for each band of each channel for the 24 hour period.

The output format is shown in Figure 37. But more important, it is designed to take the calibration factors for all bands of all channels on a given tape and multiply each data word by the appropriate calibration factor. This decreases the human element in calibration procedure, saves time and increases accuracy of results. Another computer program has been developed to accomplish monthly summaries of data in each band-channel combination, and to provide sums and means to aid in analysis. The output format of this program is shown in Figure 38.

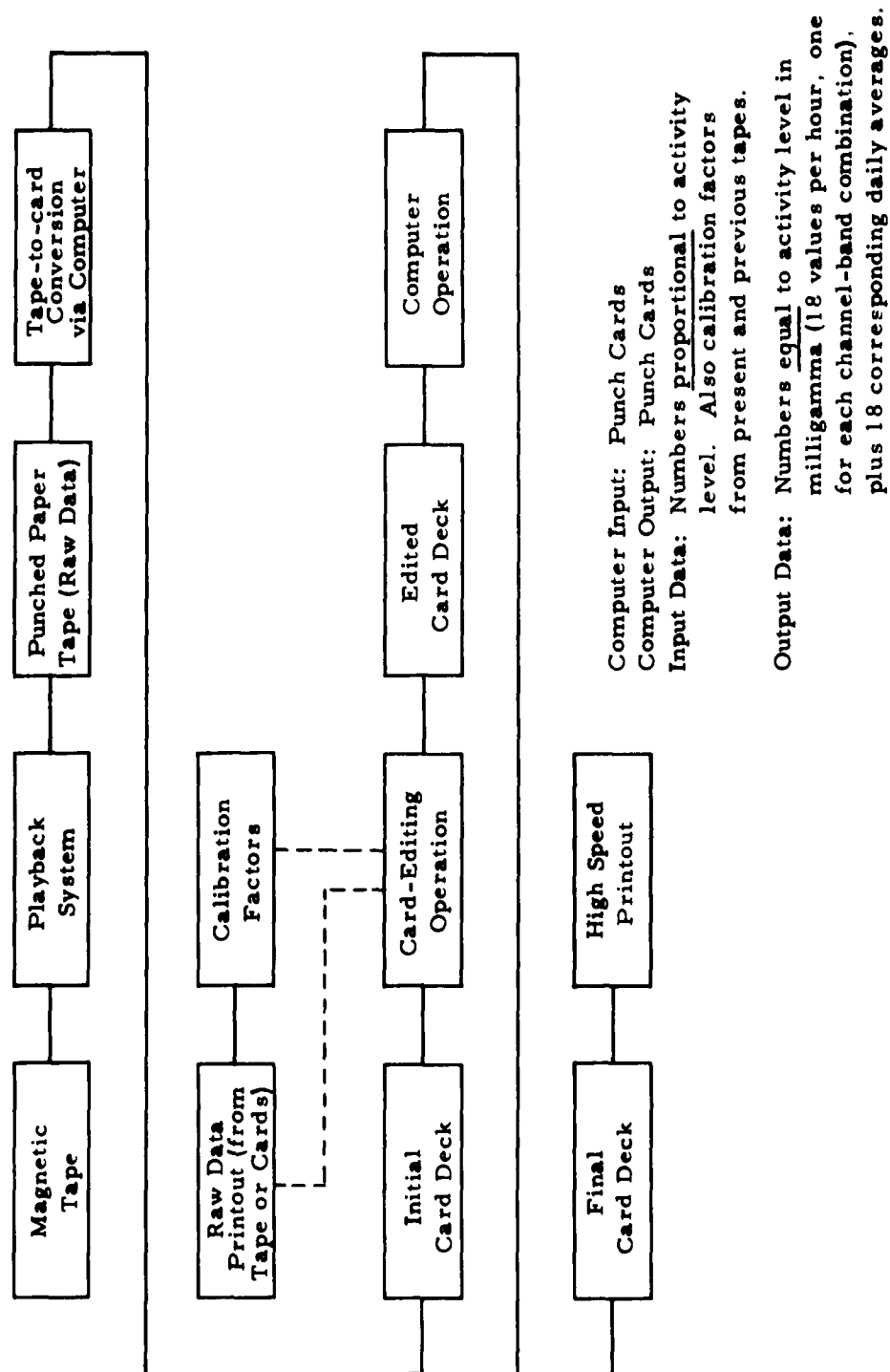


Figure 36. Data Processing System Based on Punched-Card Editing, Response Calibration By Computer, and High-Speed Printout

DENVER		CHANNEL-												
YR	DAY	HR	I						II			III		
			A	B	C	D	E	F	A	B	C	D	E	F
59	334	00	a ₁	b ₁	c ₁	d ₁	e ₁	f ₁	a ₁	b ₁	c ₁	d ₁	e ₁	f ₁
59	334	01	a ₂	b ₂	c ₂	d ₂	e ₂	f ₂	a ₂	b ₂	c ₂	d ₂	e ₂	f ₂
59	334	02	a ₃	b ₃	c ₃	d ₃	e ₃	f ₃	a ₃	b ₃	c ₃	d ₃	e ₃	f ₃
***	***	**	**	**	**	**	**	**	**	**	**	**	**	**
59	334	21	a ₂₂	b ₂₂	c ₂₂	d ₂₂	e ₂₂	f ₂₂	a ₂₂	b ₂₂	c ₂₂	d ₂₂	e ₂₂	f ₂₂
59	334	22	a ₂₃	b ₂₃	c ₂₃	d ₂₃	e ₂₃	f ₂₃	a ₂₃	b ₂₃	c ₂₃	d ₂₃	e ₂₃	f ₂₃
59	334	23	a ₂₄	b ₂₄	c ₂₄	d ₂₄	e ₂₄	f ₂₄	a ₂₄	b ₂₄	c ₂₄	d ₂₄	e ₂₄	f ₂₄
AVERAGE			M _a	M _b	M _c	M _d	M _e	M _f	M _a	M _b	M _c	M _d	M _e	M _f

Notes: 1. $M'_a = \frac{\sum_{i=1}^{24} a_i}{24}$, etc.

Figure 37. Basic Output Format for Data From System of Figure 36

Monthly Summary of Data for
Individual Band-Channel Combinations

Station: Shickley Channel: I (North-South Sensor)
Month: July 1961 Band: B (1.8 to 3.6 cps, $f_0 = 2.75$ cps)

Day	Hours				.	.	.	.	.	.	Daily Sums	n	Daily Means
	00	01	02	03									
1	b1	b2	b3	b4	.	.	.	.	.	.	xxx	xx	xx
2	b1	b2	b3	b4	.	.	.	.	.	.	xxx	xx	xx
3	b1	b2	b3	b4	.	.	.	.	.	.	xxx	xx	xx
4	b1	b2	b3	b4	.	.	.	.	.	.	xxx	xx	xx
.
.
29	b1	b2	b3	b4	.	.	.	.	.	.	xxx	xx	xx
30	b1	b2	b3	b4	.	.	.	.	.	.	xxx	xx	xx
31	b1	b2	b3	b4	.	.	.	.	.	.	xxx	xx	xx
Hourly Sums	xxx	xxx	xxx	xxx	.	.	.	.	.	.	XXXX		
n	xx	xx	xx	xx	.	.	.	.	.	.		XXX	
Hourly Means	xx	xx	xx	xx	.	.	.	.	.	.			XX

Figure 38. Format of Monthly Summary of Data for Individual Band-Channel Combinations

V. ANALYSIS AND INTERPRETATION OF DATA

At the start of this program, it was recognized that lightning discharges contributed a major portion of the natural magnetic fluctuations occurring in the 1 to 50 cps range.³ It was also expected that there would be some correlation between geomagnetic disturbance and the fluctuations at the lower frequencies near 1 cps. The transition range between thunderstorm activity, which was expected to be the dominant source at frequencies above about 5 cps, and ionospheric sources related to geomagnetic activity, which are dominant at frequencies below about 0.1 cps, had never been adequately investigated. Intervals of high fluctuation levels at auroral zone stations in the range 3 to 45 cps which were related to geomagnetic disturbance and began a few hours before the start of the main disturbance at lower frequencies had also been reported^{3,4} and were of considerable interest.

During the course of field station operations, a number of special types of signals identifiable by their waveforms have been observed. In addition to quasi-sinusoidal wavetrains of constant frequency in the frequency range of about 1 to 4 cps which resemble the "geomagnetic oscillations"⁵ long studied at lower frequencies, wave trains of slowly-varying frequency which resemble the "hooks" and other characteristic waveforms which have been studied at considerably higher frequencies ("VLF Emissions")⁶ occur. Judging from the number of occurrences during the very limited intervals when observations of this type were made, such signals are not uncommon in the 1 to 50 cps range, and their study would be of considerable scientific interest. However, these special signals do not usually affect the average 15-minute interval activity levels appreciably and cannot, therefore, be studied by the data reduction techniques so far developed under this project. The magnetic tape recordings which have been accumulated will, however, be valuable for such studies if appropriate data reduction equipment can be obtained later.

Early in the study of the reduced data, it was found that there were intervals of high activity levels in the 1 to 2 cps band of magnetic fluctuations which could not be attributed to any of the expected sources, and preliminary investigations indicated that they might be related to meteor activity. If this were established, it would necessitate revision of some of the current ideas concerning hydromagnetic processes in the lower ionosphere. Considerable effort has therefore been devoted to obtaining additional observational evidence concerning this relationship.

The study of the data obtained and reduced under this project has been a joint activity of the Denver Research Institute and the Geophysics Research Directorate as was the field recording program.

A. Fluctuations of Thunderstorm Origin

As expected, even the first preliminary analysis of the early reduced data indicated quite clearly that the major source of the fluctuations in the 1 to 50 cps range was world wide thunderstorm activity,⁷ and this conclusion has been confirmed and broadened by all later analyses of larger amounts of the reduced data.^{8, 9, 10} Thunderstorm activity is predominantly a low latitude phenomenon which shifts northward during the summer months and southward during the winter months. Contours of the geographic occurrence of thunderstorm activity for the different seasons of the year have been published.¹¹ The three main thunderstorm centers of the earth are the land-masses Africa-Europe, the Americas, and Asia-Australia, and the diurnal variation of the thunderstorm activity in each of the three centers is a function of local time, reaching a maximum at about 4 P.M. Thus, the average diurnal and seasonal variations of the source are approximately known, and since the diurnal and seasonal variations of the observed magnetic fluctuation levels clearly indicate a direct relationship, they may be used to deduce the attenuation rates of the thunderstorm signals as they are propagated in the earth-ionosphere waveguide. It was found that the minimum attenuation occurred for the 10 cps band (6.8 to 14.0 cps), for which comparatively little variation in signal level occurred either with time of day or season of the year. At higher frequencies, these variations were somewhat larger; at frequencies below about 7 cps, these variations were much more pronounced. This suggested resonant modes of the earth-ionosphere waveguide cavity first proposed by Schumann.¹² However, the octave bandwidths used in the analysis were too broad to resolve the individual modes and since the frequency of the fundamental mode for the case of the actual, non-idealized ionosphere could not be accurately calculated, the evidence for the resonance was not considered conclusive in early 1960.⁸

Balser and Wagner¹³ have analyzed a small sample of data taken using a vertical antenna detector; they used digital analysis with equivalent 1 cps bandwidths and averaged over 15 minute samples and were able to resolve the first five resonant modes of the cavity at 7.8, 14.1, 20.3, 26.4, and 32.5 cps. Since the frequencies of the first two modes lie within the 6.8 to 14 cps octave band, the results of Balser and

Wagner, combined with the more extensive data of this project, indicate that the resonant modes are a regular propagation feature in this frequency range. Recently, two of the Denver tape recordings have been re-transcribed and sent to GRD where selected samples were analyzed on a Kay Electric Co. Sonograph. The results of this narrow-band analysis tend to confirm the general features of the results described above. However, it was observed that the signals tend to come in bursts a few seconds long, and it appears that the resonant frequencies may vary by ± 1 cps or more from one burst to another.¹⁴ These variations were apparently averaged out in the 15-minute samples of Balser and Wagner. It is apparent that the fine structure of the resonance effects requires further careful study. When simultaneous data from different stations operated under this project are compared in more detail, more precise information on many features of the propagation should result.

B. Fluctuations Related to Geomagnetic Disturbance

An unexpected result has been the fact that at middle-latitude stations very little of the activity, even in the 1 to 2 cps band, appears to be related to geomagnetic activity as measured by the K indices of the standard magnetic observatories. At most times at these latitudes, thunderstorm activity is the predominant source even at the lowest frequency studied here. More careful analysis than has yet been done will be required to evaluate the small contributions from geomagnetic disturbance. Very little data have yet been examined from the higher latitude stations where the effects of magnetic disturbance would be expected to be greater.

C. Fluctuations Related to Meteor Activity

The question of magnetic effects associated with meteor activity has been controversial. Kalashnikov¹⁵ reported some correlation between the rate of occurrence of short pulses on sensitive records of the vertical component of magnetic field intensity on the dates of meteor showers. Hawkins,¹⁶ however, found only such correlations as might be expected statistically.

Early in the study of the data obtained under this project, it was observed that there were occasional large increases in the signal level in the 1.5 cps band (1 to 2 cps) which could not be attributed to thunderstorm activity since they were not associated with increased activity at

frequencies above 4 cps; weaker accompanying increases in level were sometimes observed in the 2.6 cps band (1.9 to 3.7 cps). These increases did not correlate with the K indices of geomagnetic activity, but it did appear that they might correlate with meteor activity.

Visual observations of meteor activity during the Geminid shower were made at the Denver (Mt. Evans) station in December 1959. Very strong magnetic activity in the 1.5 cps band appeared to correlate well with the meteor observations on the night of 12-13 December 1959, the peak of the meteor shower, but on other nights when the Geminid shower was active, the magnetic activity remained low. A comparison of the Denver 1.5 cps magnetic data for October, November, and December 1959 with statistical results of published meteor counts for previous years was then made and yielded further support for the correlation.¹⁷ Comparison of the Denver magnetic data for December 1959 with meteor count data obtained from the National Bureau of Standards for the same time interval also offered support for the hypothesis of correlation with meteor activity,¹⁸ and observations of the waveforms on the tape recordings showed that the increased magnetic fluctuation levels attributed to this source consisted of quasi-sinusoidal wavetrains at frequencies of about 1.5 cps.¹⁹

These results do not actually conflict with the results of Hawkins¹⁶ who made wide-band observations in New Mexico during the summer months. The inclusion of higher frequency signals from thunderstorm activity would have masked any meteor signals rather effectively in his data; also, his analysis was based chiefly on vertical component recordings, while the meteor signals discussed here appear chiefly on the horizontal components (stronger on the N-S component than on the E-W component) and are very weak on the vertical component records. The much narrower band analysis used for the Denver data removed most of the thunderstorm fluctuations. Even so, the increased signal levels here attributed to meteor activity can usually be definitely identified as of non-thunderstorm origin only in night-time data during fall and winter when all thunderstorm activity is at a great distance from the recording station. Waveform analysis, of which very little has so far been done, would be required to effect the separation at other times. The characteristic waveforms can also be identified by ear when the recordings are played back through a loud-speaker, since the original 1.5 cps signals appear at 150 cps at playback. The results reported here are at variance with those of Kalashnikov¹⁵ who reported "random" pulses rather than the wavetrains observed in this project.

The early results described above strongly suggest hydromagnetic resonance in the ionosphere as the mechanism by which the meteor activity produces the magnetic signals. Also, since the meteors expend almost all of their energy in the E and D regions of the ionosphere, the hydromagnetic effects would also be in the lower ionosphere. The observational data thus appears to be in disagreement with present hydromagnetic theory, and more conclusive observational data are needed.

In December 1960, an attempt was made during the Geminid meteor shower to obtain a measure of local meteor activity at the Denver (Mt. Evans) station by monitoring the reflection of the signal from a Denver radio station at approximately 100 mc. No useful local meteor data were obtained, but meteor rate data were later obtained from the Central Radio Propagation Laboratory, NBS, through the courtesy of Mr. C. E. Hornback. Comparison with the Denver magnetic data again yielded support for the connection between 1.5 cps magnetic fluctuations and meteor activity.¹⁴

In order to obtain the best possible evidence concerning the relationship, it was desirable to have the magnetic field measuring equipment directly under the area of the ionosphere in which the meteor activity is being measured. In early 1961, a six-month subcontract was negotiated with Section 85.20 of CRPL, NBS, to provide DRI with continuous recording of meteor-scatter transmission of a 50 mc CW signal which would serve as an index of meteor activity. The radiation from a transmitter at Long Branch, Illinois, is beamed upward at an angle of 40° above the horizontal toward Boulder, Colorado, where the receiver is located. Shickley, Nebraska (40.5°N, 97.7°W) is at the midpoint of the radio path, and CRPL also provided facilities at their Shickley site to house the magnetic recording station.

Recording of the scatter transmission data started on 6 April 1961 and continued through 30 September 1961. It is planned to resume recording during December 1961 and January 1962 to test correlation with the Geminid and Quadrantid meteor showers. The characteristics and coordinates of the transmitting and receiving stations are shown in Table 1. A typical recorded trace is shown in Figure 39. The quantity recorded as a measure of received signal strength by the Esterline-Angus meter is the AGC voltage of the receiver, the time constant of the AGC circuit being 12 seconds. The base level of this signal as received at Boulder is low, but the level increases sharply when meteor-produced ionization provides a reflecting surface.

TABLE 1

Characteristics of Ionospheric Forward Scatter Path,
Long Branch, Illinois to Boulder, Colorado

Frequency	49.880 Mc/s
Transmitter:	
Location	Long Branch, Illinois
Coordinates	40°13'N, 90°01'W
Power to antenna	2 kilowatts
Azimuth to receiver	274°30'
Path Midpoint:	
Location	Shickley, Nebraska
Coordinates	40°26'N, 97°30'W
Geomagnetic latitude	50°N
Receiver:	
Location	Boulder, Colorado
Coordinates	40°08'N, 105°15'W
Azimuth to transmitter	85°30'
Surface Path Length	1295 Km, 805 miles
Antennas:	
Transmitting and receiving	Long wire rhombic
Elevation of maximum of main lobe	4.6°
Half-power beamwidth	6°
Plane wave gain relative to dipole at same height	19 decibels
Impedance at receiver terminal	50 ohms
Esterline-Angus records:	
Chart speed	3 inches per hour
Chart time	Mountain Standard
Date markings	Near noon, before and after midnight
Transmitter breaks	2 minutes starting each hour and half-hour
Signal calibrations	-30 to +40 decibels above one micro- volt using a 50-ohm signal source
Noise calibrations	0 to 20 decibels above KTB using a 50-ohm noise source
Receiver voltage recorded	AVC voltage with 12 second time constant

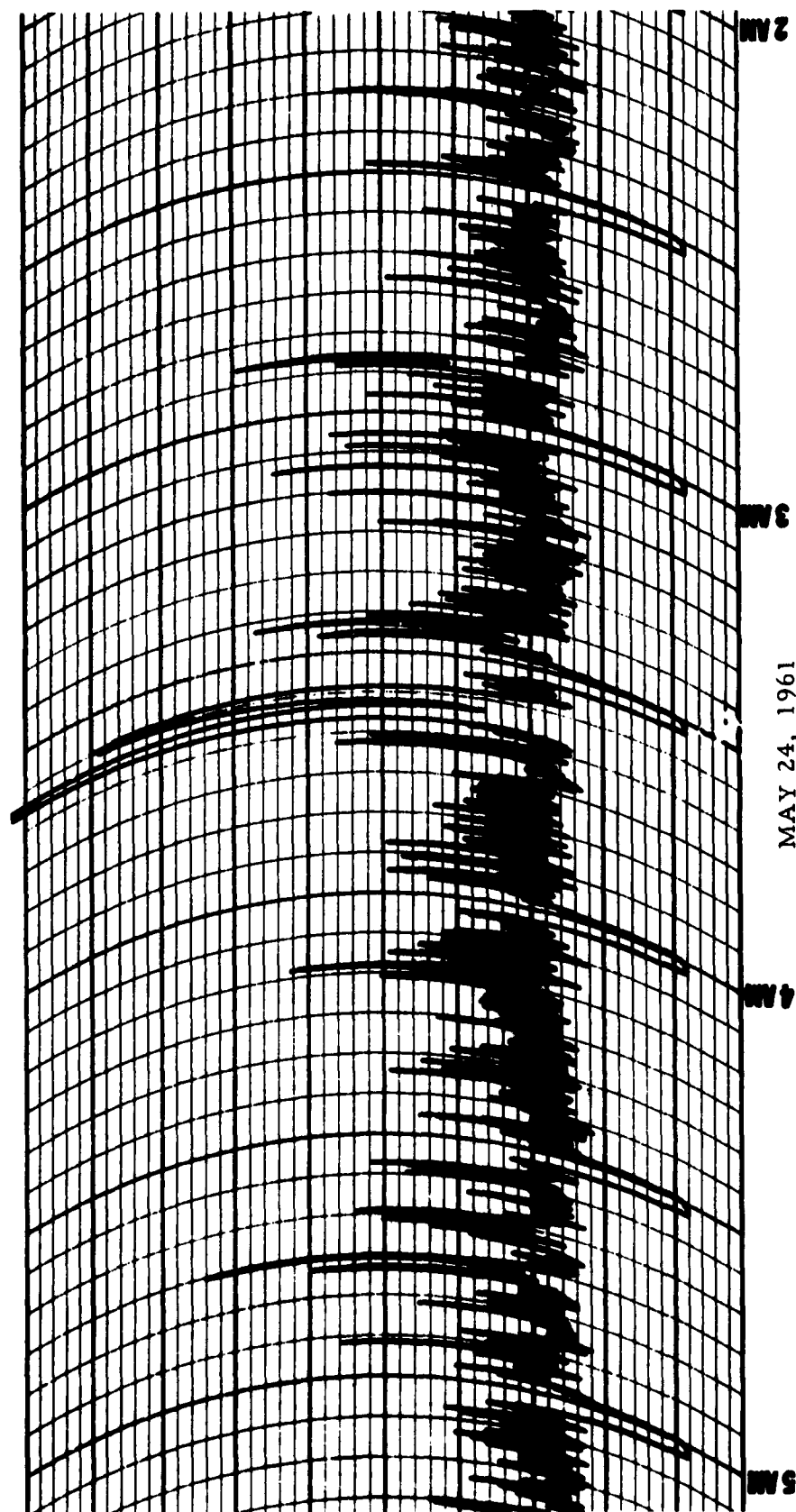


Figure 39. Typical Meteor-Scatter Record

The method of preliminary scaling of the meteor activity records is to select the one hour of greatest activity from each 24-hour interval and to scale the data for that hour to provide a rough summary of activity with time. Comparison with the magnetic records from Shickley (few of which have yet been reduced) should permit selection of times for which detailed scaling should be done. The method of scaling used so far on the meteor activity records is a simple count, by hours, of the number of excursions of the trace above specified, calibrated signal levels. A considerable refinement of this method has been developed by CRPL in its Meteor-Burst Propagation Project,²⁰ and this method may be used for the later, more detailed scaling of the records.

VI. FUTURE OBJECTIVES

Although this is a final report for contractual reasons, the program started under this contract is to continue under a new contract. A large quantity of magnetic tape recordings which constitute a reservoir of information on geomagnetic fluctuations has been accumulated under this contract. A good start on the reduction and analysis of the data has been made, but much remains to be done. The further reduction and analysis of the accumulated body of data will constitute the basic purpose of the new contract. Additional operation of one or two recording stations will be for limited time intervals and for specific purposes.

The reduction and analysis will be directed toward further study of the relationships between the magnetic fluctuations and their sources such as thunderstorms and meteor activity. A more detailed search for relationships between the fluctuations and geomagnetic disturbance will be conducted. It has become apparent that narrow-band frequency analysis (bandwidth about 0.1 times midband frequency) of limited samples of the data are needed to supplement the present wide-band (octave bandwidth) studies. Suitable methods of analysis are being investigated. Some of the desired information can probably be obtained by substituting narrow-band filters for the octave filters in the present analysis equipment. Each tape recording would be run through the equipment a number of times, the frequency of the filters being changed for each run, in order to cover the full frequency band. However, in order to extract useful information on some of the special waveforms mentioned in Section V above, a completely different approach would be required. A device such as the Raytheon Rayspan Analyzer would be desirable, but will be financially impractical in the immediate future. Theoretical calculations of attenuation factors for hydromagnetic waves in the ionosphere and a study of possible resonance mechanisms will be made in connection with the meteor data. A continuing objective will be further improvement of data recording and reduction instrumentation and of the computer and data-processing procedures.

VII. PERSONNEL

At the initiation of the contract in early 1957, the work was under the direction of Dr. A. R. Jordan. He was assisted by Charles E. Collins, Donald Dubbert and Robert Davis in the development of the basic recording system. Construction of the early station equipment was done primarily under Collins' supervision. James M. Chapman developed the equipment and procedures for calibrating the recording system using the cube coil.

Dr. Jordan left DRI in the summer of 1957 and Mr. Collins became project supervisor. Franklin E. White became associated with the project in the summer of 1958 and worked with Collins until Collins left DRI effective 30 April 1959. During this period, Mr. White had directed the project for several months. Charles A. Phillips joined the project full time in February 1959 and directed it until late 1959 when Dr. Alvin W. Jenkins joined the project as principal investigator. Phillips continued to direct the day to day activity of the project and Dr. Jenkins functioned primarily in a scientific advisory capacity. Phillips left DRI as of 1 September 1960 and was succeeded by George L. Mason. Dr. Jenkins left DRI as of 1 September 1961 and Mason became project supervisor. The other members of the present project staff are Herbert C. Westdal, Operations Specialist, Charles R. Higgins, Research Technician, and Forrest F. Carhart III, Research Technician.

John van Allen was largely responsible for the design of the data reduction system and for a number of recording system modifications. Construction of the reduction and recording systems was accomplished primarily by van Allen and James S. Smith.

VIII. PUBLICATIONS AND PAPERS

Items 7, 8, 9, 10, 14, 17, 18 and 19 in the list of references below were either prepared under this contract or were based on data obtained under this contract.

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APPENDIX

APPENDIX

Chronology of Recording Operations

The periods during which recording operations were conducted at the various stations are summarized in Figure 40 and discussed in detail in the following sections.

1. The Puerto Rico Recording Station

The Puerto Rico site was negotiated in late 1957 with the National Bureau of Standards and was to be operated by the personnel of their ionospheric station at Ramey Air Force Base. Equipment was initially installed in late January 1958 by Mr. Collins of DRI. Circuit modifications and installation of new sensor coils, as indicated by the early field tests, was accomplished by Mr. Collins in April 1958, and the station was in operation from 3 May 1958 until 3 February 1959. At that time the data reduction equipment had been completed far enough to permit check runs on the tapes from the field stations, and tests showed that the signals were not getting onto the tapes in usable form; the defect had not been detectable by the station operators. An attempt was made in May 1959 to reactivate the station, but the equipment had become noisy. By that time, NBS personnel were busy with other programs which had been added at their station and were justifiably annoyed by the waste of their previous efforts. The station was therefore shut down, and the equipment later returned to Denver and was installed at Huancayo, Peru, after modification and repair at DRI. No usable tapes were obtained from the Puerto Rico station.

2. The Fort Devens Recording Station

The Fort Devens recording equipment was constructed at the Denver Research Institute and shipped to Mr. Elwood Maple of the Geophysics Research Directorate in December 1957. At that point, responsibility for operation and maintenance of the station passed to Mr. Maple; DRI was to be responsible for the reduction of tapes recorded there.

As previously indicated, much of the early field testing was done at the Ft. Devens station, and the first tape was recorded 1 May 1958 after the early instrumentation problems were solved. The station lost a total of only 29 days recording time from 1 May 1958 to 17 January 1959. From 18 January 1959 to 12 February 1959, the station was deactivated due to power supply trouble and noise problems. From 13

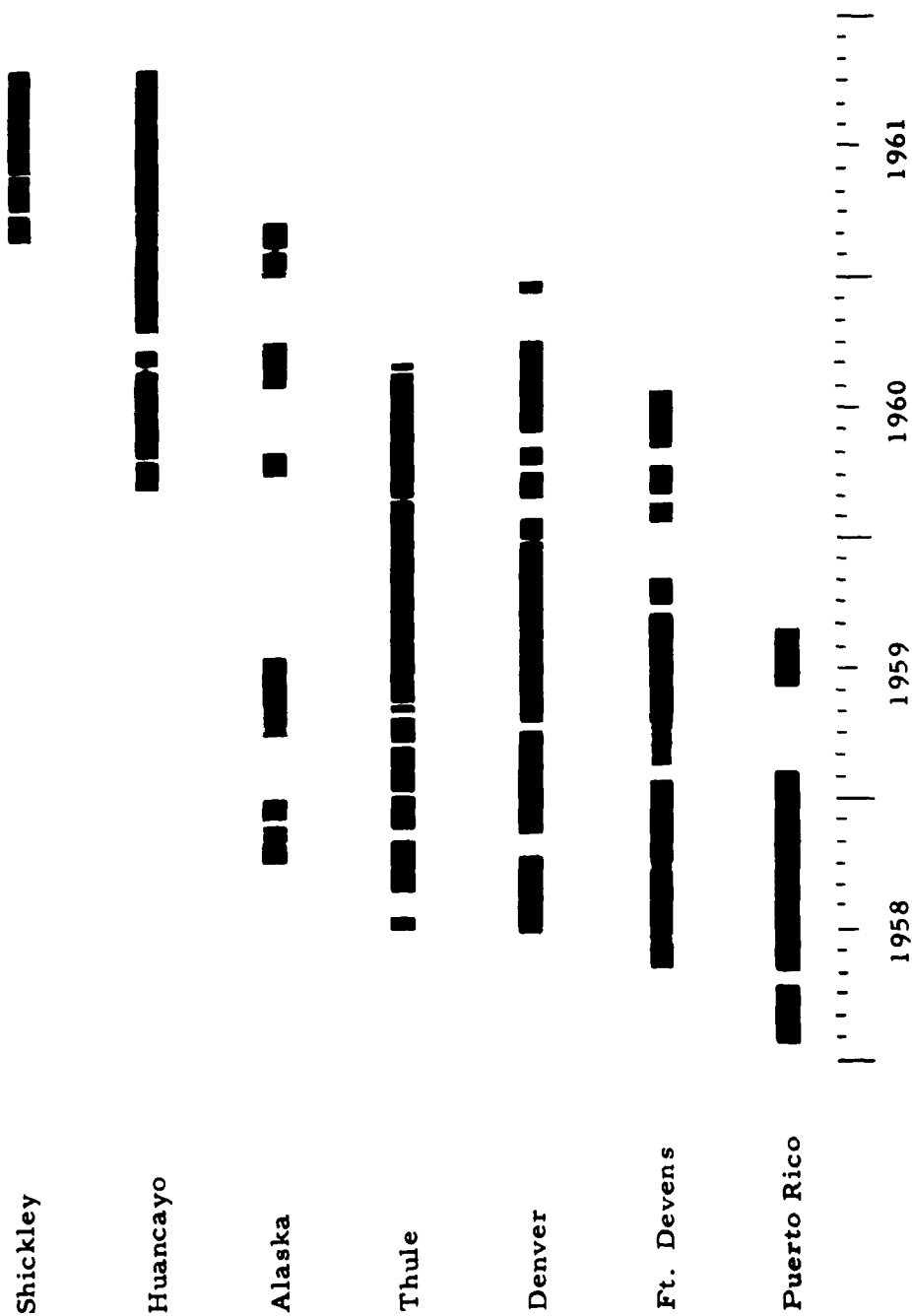


Figure 40. Periods of Recording

February 1959 to 1 June 1959, there were alternate intervals of recording and down time while the system was being checked for performance; during this interval the station was down for a total of 55 days. From 1 June 1959 through 26 October 1959, operation was essentially continuous except for a four day interval starting 10 September 1959 when the Channel III modulator was being repaired. On 26 October 1959 the special drive motor in the Ampex tape transport failed, and almost three months elapsed before a replacement could be obtained. Recording was resumed on 19 January 1960 and continued until the station was shut down permanently on 25 July 1960.

Extrapolating from the tapes so far reduced from Fort Devens, probably two thirds or more of the total of 162 tapes recorded there will be reducible to useful data.

3. The Alaska Recording Station

A subcontract was negotiated with the Geophysical Institute, University of Alaska, to furnish a site with heated room for the recording equipment and a technician to maintain the equipment and change tapes. The site chosen was 26 miles southwest of College, Alaska. Equipment was set up by Mr. Collins of DRI in March 1958 but was not operational until 1 October 1958 because of timer trouble and the other early instrumentation problems previously described. By January 1959, sixteen tapes had been received without data sheets; lacking the information on recording times, etc., it was impossible to determine tape chronology.

By July 1959, the station was still producing poor recordings on which the signal-to-noise ratio was too low, particularly at the lower frequencies. This station exemplified the many difficulties which can develop in such operations. The technicians who operated the equipment were unable to handle adequately all the difficulties which developed, and turnover of professional personnel had left no one with specific interest in the project. In addition, the voltage regulation of the ac power at the field site was extremely poor. When the voltage dropped below 95 volts, the ac voltage regulator could not correct it, and the tape transport stopped. The power problem also contributed to instrument noise and accentuated other problems. In a phone conversation in late July 1959 between DRI and Geophysical Institute representatives, the position was taken that they (GI) could not do any major repair work and that the equipment should be rebuilt. However, it was agreed to shut down the station and use the time normally used for changing tapes toward making modifications. This attempt proved unsuccessful, and the console containing the recording equipment was sent to DRI for modifications, arriving early in November 1959.

Since data from an auroral zone station was considered important, another attempt was made with the College station. A new subcontract was negotiated, and Dr. Jenkins, DRI Project Supervisor at that time, went to College to activate the station with the rebuilt equipment. Recording began 24 March 1960, but more instrument trouble soon developed; the filament power supply failed about the middle of April 1960, and the station was shut down while the power supply was shipped to Denver, repaired, and returned. Recording was resumed at the end of July 1960 and continued until 20 September 1960. A further 3-month subcontract was negotiated, and Mr. Van Allen, DRI electrical engineer, went to College, Alaska, in late December 1960 to service the equipment and put it into operation again. Timer trouble prevented satisfactory recording operation until the middle of January 1961. After this time, there continued to be erratic carrier breaks and tape slippage, apparently caused by ac power troubles, until the station was finally deactivated on 15 March 1961.

The tapes recorded during 1958 were unusable because no data sheets were kept; those recorded during the early portion of 1959 have a low signal-to-noise ratio and will probably be useful only for a search for possible special events. During the period from 24 March 1960 to 27 December 1960, 18 tapes (approximately four days each) were recorded, while the two and one-half month period from January 1961 to 15 March 1961 resulted in 16 tapes. Because of the tape stoppages and other troubles at the station, reduction of these tapes is a slow process which has been deferred in favor of other stations; the amount of usable data from the station has therefore not yet been definitely established.

4. Thule Recording Station

The recording equipment for the Thule station was shipped from DRI to GRD in May 1958. Mr. Maple activated the station on 28 June 1958; the responsibility for the operation and maintenance of this station has been his. The first three tapes were recorded from 27 June 1958 through 11 July 1958 when the equipment was shut down for repairs. From 17 August 1958 the station recorded until 25 August 1960 with a total down time of but 47 days. The success of this station is due to Mr. Don Smart of GRD through July 1959 and thereafter to Mr. Charles Sawyer and Mr. John Allen Jones of the American Geographical Society who operated the GRD Geopole Station under contract with GRD. They maintained operations under great difficulties of weather, erratic ac power sources, and isolation from sources of supplies.

The Thule site was far from ideal. Many periods of sustained high winds caused mechanical vibration of the sensors and thus invalidated the data. There were a number of independent, diesel-generator power systems distributed over the airbase area which generated noise at approximately 30 cps which will often make the highest frequency band of the data unusable; the man-made noise level at about 1 cps was also often a disturbing factor.

Because of the location of the station, it was thought that increased signal levels might be associated with unusual solar-geophysical events, and the system was therefore often operated at low gain settings. This factor, combined with the limited dynamic range of the magnetic tape recordings, will make some of the records unusable.

On 18 February 1960, the vertical detector was replaced by a 100-foot square loop of five-conductor cable. Its #14 conductors formed a five-turn loop; calibration current was carried by the cable shield. Preliminary examination of the Channel II output indicated that this greatly improved the Channel II data.

The station was deactivated on 26 August 1960, and the equipment shipped to Denver. Many of the components were subsequently assembled into the system which was shipped to Antarctica in early November 1960.

Of the total of 168 tapes received from this station, a high percentage, possibly half, may not be reducible to useful data because of low gain settings, wind noise and man-made noise, and timing troubles.

5. Denver Recording Station

The site for the Denver station was the Doolittle Ranch, Mt. Evans, forty-five miles west of Denver. The site was located on property administered for the Inter-University High-Altitude Laboratory by the University of Denver. It was acquired in December 1957, and was initially used to field-test the other stations as they were completed.

The Denver station started operation in mid-June and recorded its first tape 28 June 1958. It recorded continuously until 4 October 1958, but was shut down then until 11 November 1958. There were still noise problems, and to some degree they persisted until July 1959.

From 12 November 1958 until 28 January 1960, recording was continuous, except for 24 days. Of these 24 days, 11 were used to improve the noise problem at the Denver station. This period was from 26 June 1959 - 6 July 1959.

Due to a combination of heavy snow, component degeneration, and battery troubles, the station lost 48 days recording from 29 January through 5 May 1960. From 5 May through 26 May 1960 the timer was rebuilt. From 26 May until 3 October 1960, the station recorded continuously. It was deactivated at that time.

It was reactivated temporarily for continuous recording 8 - 15 December 1960 during the Geminid meteor shower.

After 15 December 1960 it was transported to DRI for modification and repair, to be set up later at Shickley, Nebraska.

DRI personnel serviced and maintained the Denver station throughout its total recording period. From this experience several conclusions were derived which were of general application to the procedures involved in running any recording station using this equipment. First of all the ultimate goal of the recording operation should be kept in mind at all times, namely to get the desired data on the tape in such form that it is reducible to numerical values. Operating procedures must be developed and performed with this purpose in view. Signal to noise ratio is highly important and checking procedures must locate and eliminate noise sources so the system is operating at its best during all recording periods. Ideally, a full set of calibrations should be present on every tape; practically it has been found that two calibrations per tape in a regular sequence of frequencies is adequate in most cases. There should be no gain changes for which immediate recalibrations are not performed. Finally, complete and accurate records covering all phases of the recording operation are imperative. All of these requirements must be met if the reduced data is to be fully meaningful, and is to be obtained without excessive expenditure of time in the reduction process, if at all

A total of 191 tapes were recorded at the Denver station. Of these, 8 are totally unusable. Possibly 45 more are of dubious quality.

6. Huancayo Recording Station

Negotiations for setting up this station were initiated in September 1959 between Charles A. Phillips, Jr., DRI project supervisor at that time, and Dr. Albert A. Giesecke, Jr., Head of the Instituto Geofisico de Huancayo. The equipment from the Puerto Rico station arrived at DRI in November 1959. It was extensively modified and rebuilt and shipped to Huancayo early in February 1960.

The station was activated on 7 March 1960 and recorded until 17 April 1960 when it was shut down for minor modification and maintenance for six days. The lead-in cables from the sensor coils were buried in waterproof pipe, since it had been determined that wind caused spurious signals when the cables were suspended above ground. The amplifiers were also checked over completely, and doubtful connections were resoldered, etc. This is but one example of the excellent work which the Instituto Geofisico has consistently done to insure validity of its recorded data.

Recording was resumed on 23 April 1960, and continued until 15 August 1960. Beginning about 8 July through the middle of September 1960, intermittent power failures occurred which may make about 9 reels of magnetic tape of doubtful value for reduction.

In October 1960 the Instituto Geofisico reworked the timer using a time base independent of line frequency. Their modification was a substantial improvement, and there has been no further problem with timing on the Huancayo tapes.

The original subcontract was to run until 30 September 1960. However it was decided that a full year's recording from Huancayo was desirable, and the subcontract was extended to 31 March 1961.

From 15 September through 14 October 1960 the station was down while the new timer was being adapted for the recording equipment. From this time until 31 March 1961, the station recorded continuously.

The station was deactivated after this, but the equipment remained at Huancayo. In September 1961 it was decided to reactivate the station, to record on a continuous basis, that is, 60 minutes an hour instead of 15 minutes per hour. The Instituto Geofisico staff

reactivated the station on one week's notice. The station recommenced recording on 25 September 1961 and is to record for an indefinite period, probably for the remainder of 1961.

A total of 88 tapes have been received from Huancayo during this contract period. It is estimated presently that at least two-thirds of these will be reducible.

7. Antarctic Station

The equipment and supplies from the Thule, Greenland station were received at DRI in early October 1960. Previous to this, construction of new sensing coils, and new amplifier and modulator units, was well under way. The Thule apparatus was checked over as thoroughly as available time permitted. The system incorporating the new sensing coils, amplifiers, and modulators was then assembled and taken to the Mt. Evans site where it was calibrated and tested. The timing unit and the power supplies for B+ and 28 volts DC (all on one chassis) which were in use at Mt. Evans, were shipped as part of the Antarctic station equipment, and the timing and power supply unit used at Thule was held in Denver for rebuilding. This was done to gain time.

The main shipment for the Antarctic station left Denver by air freight on 2 November 1960 for Davisville, R. I., and was forwarded to the Antarctic on the ship "Greenville Victory". A later mailing to the Geophysics Research Directorate included additional spare parts, the rebuilt Esterline-Angus driver unit, manuals for certain units of the equipment, and copies of the overall system manual which had been completely revised and enlarged during this period. These latter items were carried to the Antarctic by the personnel who were to operate the equipment.

The equipment was to have been set up at the Byrd Satellite Station, about 40 kilometers from the main Byrd Station, which was intended primarily for auroral studies and was expected to provide a quiet site for the magnetic measurements. Because of late arrival of supplies and early bad weather, the Satellite Station was not sufficiently completed during the Antarctic summer of 1960-61 to provide adequate living facilities, and all operations there were postponed. It is expected that the Station will be completed in the 1961-62 season and that the station will be operational early in 1962.

8. Shickley Recording Station

This station was set up to investigate further the relationship between the 1 to 2 cps magnetic data and meteor showers which had appeared in earlier data. The site is leased by the Central Radio Propagation Laboratory of the National Bureau of Standards and is under the midpoint of their CW meteor-scatter radio transmission path between Havana, Illinois, and Boulder, Colorado. Dr. Alvin Jenkins and George Mason of DRI visited the site early in January 1961, and a six-month subcontract was negotiated with NBS for use of the site and facilities there and for obtaining and furnishing to DRI the meteor-scatter data. The station was set up and checked out during the period 9 to 19 February 1961, and recording was started on 19 February 1961. Mr. Jay E. Burton of Geneva, Nebraska, has been in charge of operating and maintaining the station.

There are about 10 tapes which are probably no good for reducible data. From preliminary checking of a few tapes, it is almost certain that the 20 and 40 cps bands on Channel II (vertical) will not be usable. There is a constant 30 cps signal, external to the recording equipment, at the site which effectively masks the natural signal.

Except for intermittent timer trouble during the first ten tapes, and occasional power failures, the station has recorded continually, and most of the data should be reducible with the exceptions noted.

A total of 67 tapes have been received from the Shickley station during the contract. Of these possibly 15 may be considered unusable.

9. Summary of Recording Operations

Although many early difficulties delayed the start of the field recording program, most of the intended program has been successfully completed. Adequate data samples have been obtained from the Denver, Fort Devens, Thule, and Huancayo stations, the latter being a replacement for the original Puerto Rico station. The chief deficiency in the data is the lack of a sufficiently large sample of usable recordings from a station near the auroral zone maximum. It is expected that data from the Antarctic Station, together with the limited sample from College, Alaska, would remedy this situation; as indicated above, however, logistic factors have delayed operations in the Antarctic.

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